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EXPERIMENTAL MEASUREMENTS OF MOTION CUE EFFECTS ON STOL APPROACH TASKS

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EXPERIMENTAL MEASUREMENTS OF MOTION CUE EFFECTS ON STOL APPROACH TASKS

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April 1972

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Ames Research Center
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FOREWORD

The research reported here was sponsored by the Man/Machine Integration Branch, Biotechnology Division, Ames Research Center, National Aeronautics and Space Administration. It was conducted by Systems Technology, Inc., Hawthorne, California, under Contract No. NAS2-6433 with NASA support for the experiment. The NASA Project Monitor was James Howard, the Contractor's Technical Director was Duane T. McRuer, and the Project Engineer was Robert F. Ringland.

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ABSTRACT

The results of an experimental program to investigate the effects of motion cues on STOL approach are presented. The simulator used was the Six-Degrees-of-Freedom Motion Simulator (S.01) at Ames Research Center of NASA which has ±2.7 m travel longitudinally and laterally and ±2.5 m travel vertically. Three major experiments, characterized as tracking tasks, were conducted under fixed and moving base conditions. The first was simulated IFR approach of the Augmentor Wing Jet STOL Research Aircraft (AWJSRA), the second was a similar simulated VFR task with the same aircraft, and the third a single-axis task having only linear acceleration as the motion cue. Tracking performance was measured in terms of the variances of several motion variables, pilot vehicle describing functions, and pilot commentary.

The results show that the dominant (i.e., largest and most easily discerned) effect of motion is on vehicle attitude control. Motion also affects path control, but to a lesser and more variable extent — performance improved, remained the same, or deteriorated depending upon subject, task, and controlled variable (altitude or lateral deviation). In the context of a continuous tracking task, pilots can respond to rms angular rates as low as 20 mr/sec and to rms linear accelerations as low as 0.05 g; in the latter instance pilot sensitivity to these cues appears independent of the direction of the linear acceleration. Pilot usage of linear acceleration cues in simulated flight was heavily dependent upon pilot background. For example, the altitude performance of a former helicopter pilot was sensitive to the presence or absence of a vertical acceleration cue, while a former Navy jet pilot's commentary was quite sensitive to the nature of the longitudinal acceleration cue. Finally, the pilots proved quite sensitive to anomalous simulation cab rates resulting from the residual tilt of the cab used to duplicate low frequency translational accelerations.

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SYMBOLS

a, b	Inverse time constants, coordinated washout
$a_{x_p}, a_{y_p}, a_{z_p}$	Specific forces at the pilot location in body-fixed coordinates
$\hat{a}_{x_p}, \hat{a}_{y_p}, \hat{a}_{z_p}$	Specific forces in cab coordinates
f_{c_p}	Specific force vector
g	Acceleration of gravity
g_c	Gravitational acceleration vector in cab coordinates
$\ddot{h}_d$	Altitude acceleration disturbance
k_m	Gain margin
K_a, ζ_n, ω_n	Vertical washout gain, damping, and break frequency
K_c	Controlled element gain
K_f, ζ_s, ω_s	Low pass filter gain, damping, and break frequency
K_p	Pilot gain
K_s	Scale factor for uncoordinated washout
K_R, T_{R_1}, T_{R_2}	Lag filter parameters, uncoordinated washout
K_1, K_2	Simulator compensation coefficients
K_1, K_2, K_3	Stabilizing network gains
M	Transformation matrix relating Euler angle rates to instantaneous body axis rates
N	Denotes number of runs
p, q, r	Roll, pitch, and yaw rates
$\hat{p}, \hat{q}, \hat{r}$	Roll, pitch and yaw rates of simulator cab
p_{BN}	Rolling gust velocity

T	Time constant
$T_{c/i}$, $T_{i/c}$	Direction cosine matrices relating cab to inertial coordinates and vice versa
u	Perturbational change in forward speed
V_a	Airspeed
V_{BN}	Lateral gust velocity
x, y, z(or h)	Vehicle translations
$\hat{x}$, $\hat{y}$, $\hat{z}$	Cab translations
Y_c	Controlled element transfer function
Y_p	Pilot describing function
Y_{p_h}	Pilot describing functions in altitude control task (see Fig. A-9)
Y_{lps}	Describing function of linear proprioceptive senses
γ	Flight path angle
δ_c	Column deflection
δ_p	Rudder pedal deflection
$\delta_{r_{SAS}}$	Directional SAS output
δ_w	Wheel deflection
$\delta_{w_{SAS}}$	Lateral SAS output
δ_{Th}	Throttle deflection
ϵ_{GS}, ϵ_{LOC}	Glide slope and localizer errors
ζ	Damping ratio of second-order mode
ζ_ℓ, ω_ℓ	Inertial washout damping and break frequency
λ, λ_c, λ_d	Controlled, command, and disturbance variables in single-axis tracking experiment
λ_c, λ_s	Simulator motion drive variables (see Eq. A-1)
ν	Diverter deflection

ρ^2	Ratio of correlated (with input or disturbance) power to total power
σ_x	RMS value or standard deviation of motion variable, x
τ	Effective pilot lag
$\tau_{V_{BN}}$, $\tau_{p_{BN}}$	Time constants associated with gust spectra
τ_ω	Rate washout time constant in uncoordinated washout
φ, θ, ψ	Roll, pitch, and yaw Euler angles
$\hat{\varphi}$, $\hat{\theta}$, $\hat{\psi}$	Cab Euler angles
φ_m	Phase margin
ω	Undamped natural frequency
ω_c	Crossover frequency

SECTION I

INTRODUCTION

A. BACKGROUND AND OBJECTIVES

The purpose of this report is to document the results of a recent experimental study on the effects of motion cues on STOL aircraft. The study represents a follow-on to more generalized research (c.f., Refs. 1 and 2). Here the interest is in STOL vehicles, specifically during the approach, flare, and landing phases of flight wherein the STOL aircraft, because it is in part thrust supported, has behavior significantly different from that of conventional aircraft. The study had the general objective of investigating the importance of motion cues in the STOL approach, flare and landing task. The specific airplane considered was the Augmenter Wing Jet STOL Research Aircraft (AWJSRA), a modified C-8A Buffalo. The moving base simulator was the Six Degrees of Freedom Motion Simulator at the Ames Research Center (ARC) of the NASA. The specific objectives are listed below:

- To investigate the relevance of vertical motion cues in STOL approach and landing.
- To investigate the effective angular motion thresholds in simulated flight relative to those measured on the MCRD (Man Carrying Rotation Device) at ARC.
- To investigate STOL landing simulation problems with reference to the AWJSRA.

These objectives are amplified below.

First, the reason for the concern with vertical motion cues is in part dependent upon the results of past experimental studies (c.f., Ref. 3) using the Flight Simulator for Advanced Aircraft (FSAA) at ARC. This simulator has considerable lateral travel (±15 m) and can therefore simulate motion cues in the lateral control tasks to a high degree of fidelity. However it is quite limited in its vertical (±1.5 m) and fore-and-aft (±1.2 m) travel. Past experimental results obtained with the FSAA and related to the longitudinal control task in the AWJSRA might therefore be questioned because of the limited travel. Therefore, it was thought that simulation on the Six Degrees of Freedom (6 DOF) Motion Simulator (±2.7 m laterally and longitudinally, ±2.5 m vertically) offered the potential of easing these doubts.

With regard to the second objective, the results of an earlier study of VTOL hovering (Ref. 4) suggested that the effective angular motion thresholds of the subject pilots were a strong influencing factor. These thresholds may, at least in part, be related to physiological measurements, i.e., measurements of vestibular threshold, as on the MCRD. The methodology of these measurements is described in Ref. 5. The current study sought to gain further information on these effective thresholds and their correlation with MCRD measurements on the same pilots.

There are two major problems associated with the third objective. The first of these is establishing the appropriate compromises in the design of motion washout circuits. In the previously mentioned study of VTOL hovering (Ref. 4) it was discovered that the lack of coordination between the rotational and translational motions of the simulator could provide the pilot with vehicle attitude cues which he would not get in flight. It was therefore decided to provide a coordinated motion washout in the current program. In this scheme, the simulator cab is tilted to provide the sensations of lateral and longitudinal accelerations at low frequencies while cab translations provide the high frequency sensations. In so doing, anomalous "residual tilt" rates are introduced. In most cases, the residual tilt rates are excessive unless all of the motions are also attenuated by some constant factor. The more the motion is attenuated, the smaller are the residual tilt rates. The compromise is then between excessive attenuation and excessive residual rates.

The second problem relates to VFR-IFR differences in fixed and moving base situations. Pilot comments would suggest that the presence of motion enhances the "reality" of a simulated VFR display. The results of Ref. 4 suggest that pilots can use a g-vector tilt cue proportional to vehicle attitude (if present) in an IFR situation where the necessity of scanning several instruments forces the pilot to look away from the attitude ball.

This tilt cue would presumably be less important under VFR conditions where he could obtain it visually at all times. Also, tighter control would be expected VFR, so other motion (e.g., attitude rates) could be more important. These examples suggest that, in a given simulation, motion differences (that is, fixed base to moving base differences) may be dissimilar between IFR and VFR situations.

A two-phase experimental program was planned to be consistent with these objectives. The Phase I program had as its major objective the validation of the experimental concept, while Phase II was intended to provide most of the data. The next subsection summarizes the Phase I experiment and results. Subsection C outlines the Phase II experiments, thereby guiding the reader to the remainder of this report.

B. PHASE I EXPERIMENT AND RESULTS

Prior to running the Phase I experiment (to be outlined below), an analysis of the experimental situation was conducted to estimate the effects of motion cues. An analysis of the longitudinal handling qualities of the AWJSRA, conducted under a concurrent program*, formed the basis. The analytical results predicted relatively small improvements in pilot opinion with the addition of motion cues, primarily because of relatively low control and maneuvering power in the longitudinal task. Motion would primarily affect pitch attitude control and have relatively minor effects on flight path control. There was the possibility that the pilot could obtain a small benefit from the vertical acceleration cue in the control of flight path.

The experimental task was one of straight in approach in light-to-moderate turbulence using the ILS needles as a reference; followed by visual breakout (transition to VFR), continued approach, flare and landing. The experimental setup was intended to resemble an earlier one of the

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*Contract No. NAS2-6441, "Flight Director Displays and Stability Augmentation System for the Augmentor Wing Jet STOL Research Aircraft."

AWJSRA on the FSAA. However some compromises were necessary, as noted below:

- Black-and-white TV monitor (instead of color with a collimating lens). Magnetic fields associated with the 6 DOF drive motors would throw a color image out of register.

- Centerstick (instead of column and yoke).

- Throttle and diverter on console to pilot's left (instead of overhead and to the right). The engine instruments were relocated to the left side of the instrument panel.

In addition, there was an instrument change — the three-axis attitude ball incorporated both glide slope and localizer indications while the equivalent FSAA simulation had the localizer incorporated on the compass. The details of the experimental setup are given in Appendix A.

Time averaged (over 100 sec) tracking performance was measured for fixed and moving base conditions, with and without a lateral and directional stability augmentation system (SAS) in the IFR portion of the simulated approach. Problems with the visual display system precluded obtaining any meaningful data on the VFR portion. The IFR results indicated (detailed in Appendix B) relatively small motion effects. Specifically:

- Inner loop (attitude) variables showed some improvement with motion (as expected).

- Outer loop (position) variables showed little change with motion. In fact, they deteriorated slightly, although the deterioration was not statistically significant.

- Pilot opinion suggested the motion to be barely detectable in many instances and of little tangible benefit.

An examination of the data after the conclusion of the Phase I experiment suggested two possible effects which could have confounded the measurements. The first of these was the low velocity of the ILS needles which could have made it difficult for the pilot to perceive needle rates. In effect, the setup was such that the pilot's visual velocity threshold could have limited his performance. The display's lack of sensitivity could also have led to a reduction in the performance going from fixed base to moving base if the vibration in the simulator adversely affected the pilot's ability to fixate on the display.

This suggested the second possible confounding effect which is termed, "inhibition/distraction." Here the reference is to two different things, with indistinguishable effects. Inhibition refers to the pilot's concern or worry about hitting the motion limits in the simulator. In the course of running this experiment, especially during the practice sessions, the pilot had several occasions when he hit the motion simulator limits, most often the lateral limits. This is a very upsetting experience because the pilot's cues are suddenly very wrong, viz., a sharp acceleration pulse as the cab hits the limit to bring it to a stop, followed by an oppositely directed pulse as it jerks off the limit to resume motion. The pilot's sense of identification with the simulation as being a real airplane is destroyed — his real concern is with hitting the stops. Obviously this only applies to a moving base situation. It is possible that his worry and concern, moving base, may deteriorate the results more than the motion cues might improve them. In the experiment, the possibility of hitting the limits may have caused the pilot to change his strategy such that he didn't hit the limits, and only secondly to worry about minimizing the displayed errors.

Distraction refers to the fact that the simulator tends to vibrate and rumble as it is moving around in the linear degrees of freedom. This might be expected to distract the pilot from the task at hand. Furthermore, the vibration, as indicated above, may increase the pilot's effective visual velocity threshold. Either effect might have deteriorated his performance in the experiment.

There were several additional factors which may have affected pilot performance, particularly in the lateral task. The pilot complained of an insensitive sideslip indicator and he thought the rudder pedals were "too sensitive." The force characteristics of the latter were such as to make it difficult to exert precise control about zero. These two defects were corrected for Phase II. A third defect in the simulation fidelity was a tendency for the attitude ball to stick in heading, although this wasn't mentioned by the pilot as contributing to deteriorated performance.

C. PHASE II SUMMARY AND REPORT OUTLINE

Because of the conflicting results of Phase I, a three-experiment program was configured for Phase II. A central feature in all experiments was the measurement of pilot-vehicle describing functions as well as performance and pilot opinion.

Section II, following, describes the setup, procedure and results for the first of these, a single-axis tracking experiment. This was a short, exploratory effect which was conducted while the real time digital computer simulation of the AWJSRA was being checked out for the remaining two experiments. It used simple controlled element dynamics and simulator motion in a single linear degree of freedom. The purpose was to determine if the pilot could use a linear acceleration cue in a tracking task. The answer is an unqualified yes — the measurements clearly show that the pilot can use these cues. Further, the results are virtually the same for vertical motion as for fore-and-aft motion.

The second experiment was an IFR tracking experiment and is discussed in Section III. The setup was similar to that of Phase I, that is, tracking of the ILS display in the simulated AWJSRA. Its purpose was to determine if display sensitivity or "inhibition/distraction" effects played a role in the Phase I results. The results showed display sensitivity effects to be dominant and motion effects to be relatively small.

The largest effort was on the VFR tracking experiment discussed in Section IV. The task was simulated level flight of the AWJSRA over a runway at low altitude in the presence of disturbances. The purpose was to determine motion effects in a simulated VFR task. Motion washout configurations and the presence or absence of specific motion cues were varied. Differences in the background of the two subject pilots dominated the results — the two subjects preferred different linear motion cues and had different apparent tolerances for residual tilt rates.

Overall conclusions from this research are summarized in Section V. These relate to the importance of motion cues in STOL simulation, utilization of linear acceleration cues, motion threshold effects, inhibiting and distracting effects of motion in a simulation, and certain implications for STOL moving base simulator design.

Appendix A describes the simulation of the Augmentor Wing Jet STOL Research Aircraft as used in the Phase II experiments, including the coordinated washout scheme. Differences from the setup used in the Phase I experiment are minor and noted therein.

The Phase I experimental results are covered in Appendix B. This appendix includes a summary table of the pre-experimental predictions of motion effects on the longitudinal task.

Appendix C provides supplementary information (chiefly data listings) to the Phase II experiments discussed in the main text.

Appendix D describes an Ad Hoc experiment which was performed on the AWJSRA simulation after the Phase II experiments were complete. The purpose was to determine the benefits of longitudinal motion cues in a large maneuver situation as opposed to the tracking tasks used in the Phase I and II experiments. Pilot commentary was the only measure. The results are in agreement with those in the main text with suitable allowances for differences in task. In particular, the pilots have a low tolerance for the residual tilt rates produced by a semi-coordinated washout scheme in large maneuvers (pitchover to acquire the glide slope and the flare maneuver prior to touchdown) where there is no masking effect due to simulated aerodynamic disturbances.

SECTION II

SINGLE-AXIS TRACKING EXPERIMENT

A. PURPOSE AND BACKGROUND

The purpose of this experiment was to ascertain whether or not a pilot could use purely linear acceleration cues to improve performance in a tracking task; further, to determine if there were any differences ascribable to the direction of the acceleration.

The role of linear acceleration sensing in discrete situations (e.g., engine failure detection) is well known, but past simulation studies of continuous tasks, in particular the Phase I experiment, have failed to give any positive indication that a linear acceleration cue was being used. (The rms magnitude of vertical acceleration in this experiment was approximately 0.35 m/sec^2.) One experimental study (Ref. 6) indicated that subjects are unreliable in their sensation of vertical motion, suggesting that vertical acceleration cues may be unusable in a tracking task.

Presuming that the pilot can use linear acceleration cues, there is question as to whether he is equally sensitive to vertical as opposed to horizontal accelerations. Physiological measurements (e.g., Ref. 7) would indicate no significant differences provided that the accelerations represent perturbations about a zero operating point. It might be argued that the effective threshold could be larger if the pilot is required to detect perturbations in the earth's gravitational field, i.e., with a vertical 1 g bias.

In view of these questions, it was felt worthwhile to conduct a short (i.e., five days duration) exploratory experiment wherein the task dynamics were specifically contrived to render it sensitive to the presence or absence of linear acceleration cues, provided the pilot can successfully sense and use these cues. Only brief efforts were made to optimize the experimental design based on early results. Were the experiment to be repeated, there are several changes which could be made to the basic setup as well as to the experimental variables. These will be pointed out in passing in the course of the discussion.

B. EXPERIMENT DESCRIPTION

The task was to control the simulator cab's position along one axis ($\hat{x}$, $\hat{y}$, or $\hat{z}$) at a time in the presence of a disturbance. The ILS needle display and either the centerstick or the rudder pedals were used to affect control. The controlled element dynamics were of a simple form, $K_c/s^2(s + 1)$. This controlled element has considerable lag and can be expected to require considerable compensating pilot lead. The lead can be generated either visually (as it must be fixed base) or using the linear acceleration cues to augment the visual cues when moving base. The orientation of the controls and displays was such that the pilot "chased" the display; for example, if the horizontal bar moved up, he would pull the stick back to "catch up" with the horizontal bar. In this respect the task resembles the maneuvering that the pilot must go through to return to the glide slope. When the stick was pulled back, the simulator cab moved either backwards or up, depending upon which axis was activated. The situation was similar with regard to the lateral task. If the needle moved to the right, the pilot would put in right rudder pedal in order to "chase" the needle, and the simulator cab moved toward the right. The pilot's objective was to maintain a centered position on the ILS display. This represented the desired cab position; needle motion was directly analogous to cab motion.

The five configurations for the experiment are given in Table 1. The table lists the symbols for each of the experimental configurations, the manipulator and display needle that were used, and the motion simulator's activity (either fixed base or moving in one of the three axes). Bobweight effects were unavoidably present in Configuration LON because the arm-hand-centerstick combination could move back and forth relative to the cab when the cab accelerated. These effects were minimized for the VER and LAT configurations because the control motions were perpendicular to the direction of the accelerations. In fact, this was the reason the pedals were used for control in P and LAT — to avoid the lateral bobweight effects which would be present if the centerstick were used for control. No attempt was made in this experiment to calibrate the LON configuration for the bobweight contribution. It was estimated to be relatively small.

TABLE 1

CONFIGURATIONS FOR SINGLE-AXIS TRACKING EXPERIMENT

SYMBOL	MANIPULATOR	DISPLAY (ILS)	SIMULATOR MOTION
S	Centerstick	Horizontal Bar	None
LON	"	" "	Longitudinal
VER	"	" "	Vertical
P	Pedals	Vertical Bar	None
LAT	"	" "	Lateral

The block diagram for the experiment is shown in Fig. 1. It shows a closed-loop system where the pilot effects control on a lagged element, to which is added a disturbance provided by a describing function analyzer (DFA). The latter was used to measure the system dynamics. The summed signals continue into a double integration element. Not shown in the figure is the lead compensation used (see Table A-3) to compensate for the inherent motion simulator lags. Similar compensation was used to overcome display lags of 0.06 to 0.08 sec. Ideally there should have been, at least within the frequency range of interest, a close correspondence between the gain and phase of the desired and the actual acceleration and between the cab and displayed position. The acceleration cues were contaminated, to some extent, with extraneous motion of the simulator associated with its vibratory modes; however, for this experiment there was no concern with how much "noise" there might be in addition to the "signal" in the cab's motions. No motion washouts were used — if the display needle headed off scale, the cab would hit its travel limit.

The describing function analyzer generated a random-appearing sum of five nonharmonically related sine waves whose spectrum is indicated in Table 2. The disturbance produced an error which was correlated with the disturbance within the DFA to measure the error-to-input describing function of the system. The result was mathematically manipulated to yield the

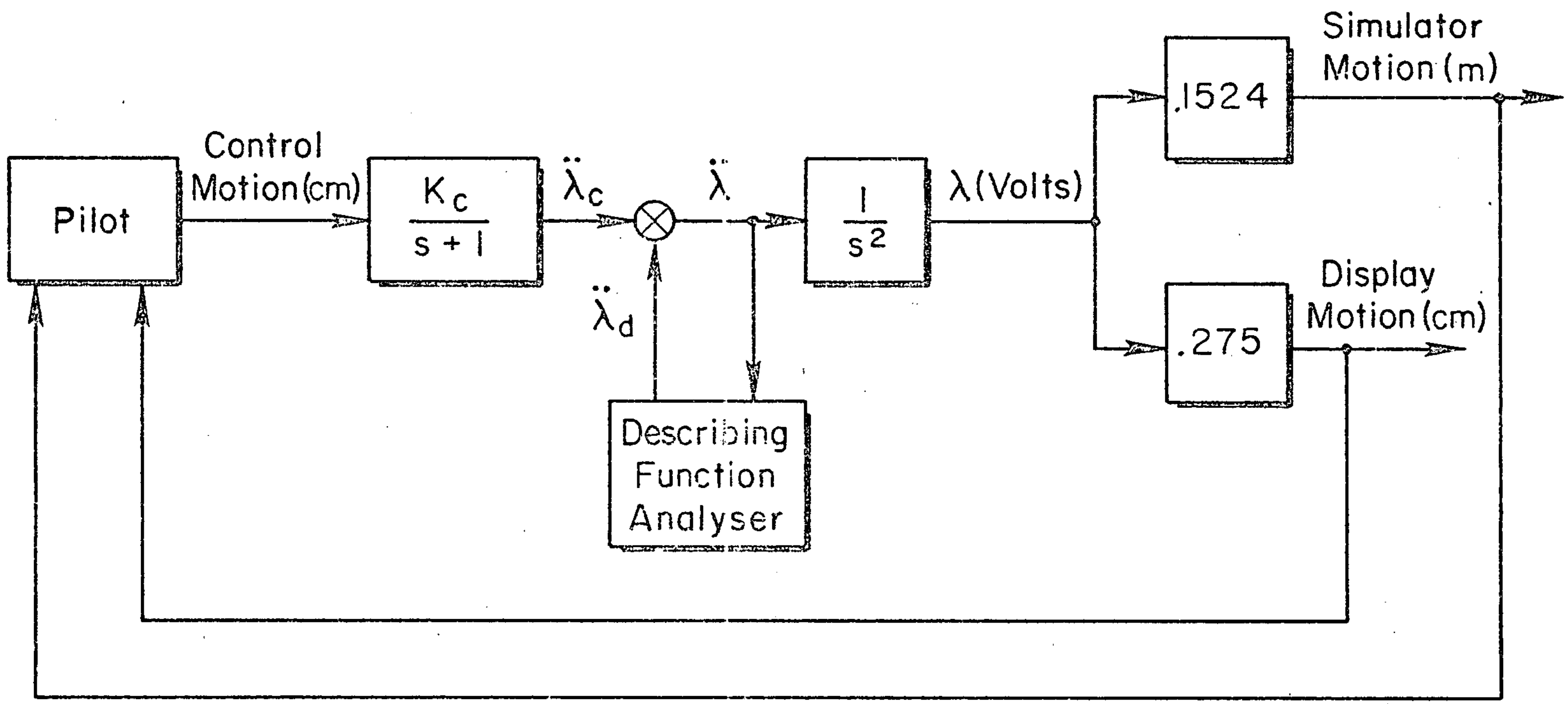

Figure 1. Block Diagram of Single-Axis Tracking Experiment

open loop describing function, Y_pY_c, where:

$$Y_c = \frac{K_c}{s^2(s+1)} \tag{1}$$

and Y_p is the effective pilot describing function in this task for visual or motion-plus-visual inputs.

TABLE 2

DISTURBANCE SPECTRUM*, SINGLE-AXIS TRACKING EXPERIMENT

FREQUENCY (rad/sec)	SIMULATOR ACCELERATION AMPLITUDE (m/sec^2)	DISPLAY AMPLITUDE (cm)
0.1886	0.0152	0.773
0.503	0.0366	0.261
1.257	0.229	0.261
3.016	0.229	0.047
6.283	0.110	0.005

Two subjects, whose backgrounds are summarized in Table 3, were used in these experiments. The major difference between subjects is EF's helicopter experience, whereas JK's experience is entirely with fixed wing aircraft. EF was the same subject used in the earlier experiments of Ref. 4 involving IFR hovering of a VTOL. Relative to the other subjects in this earlier study, he was more motion sensitive, that is, fixed-base to moving-base differences were stronger than for the other two subjects participating in that investigation.

The foregoing summarizes the essentials of the experiment. It should be stressed that the experiment was exploratory. There was insufficient time to establish asymptotic performance, or even an optimum gain, K_c, for the controlled element. Neither the controllers, whose characteristics are given in Table A-1, nor the displays were optimum for the experiment's purposes. Some improvement could be made in the describing function measures

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* $\sigma_{SIM\ ACC} = 0.345$ m/sec^2, $\sigma_{DISPL} = 0.858$ cm.

to improve measurement accuracy at low frequencies. Even with these qualifications the experimental results discussed in the next subsection are felt to be highly significant.

TABLE 3

SUBJECT BACKGROUNDS

EF:	Airline flight engineer, approximately 2500 hrs in DC-8 and B-727. Former USMC pilot with 1550 hrs as primary flight instructor; 2000 hrs in heavy helicopters (H-34), 1500 hrs as pilot-in-command. Age: 37.
JK:	Airline reserve copilot/navigator, approximately 3000 hrs in B-707. Former USN attack pilot with 1200 hrs in A-4 jets. Has 300 hrs in miscellaneous light planes. Age: 30.

C. EXPERIMENTAL RESULTS

The results were obtained in the course of five days while various simulation checks pertinent to the remaining two Phase II experiments were being conducted. There were approximately forty runs for each subject during which data was recorded, preceded by about thirty exploratory (for best gains, disturbance amplitudes, etc.) and familiarization runs for both subjects together. The protocol was to present the configurations to the subject in random order except that the centerstick tasks and pedal tasks were presented in a group — a convenience for the experimenter. There were typically ten runs (each configuration twice) in a session for each subject.

1. Pilot Commentary

First consider the pilot commentary. Table 4 paraphrases the significant remarks by subject and configuration. With regard to the centerstick tasks, the commentary suggests that the pilots improve in their ability to track, that is, in holding the needle centered, when they are in moving-base condition. However, there is very little difference between having the simulator move back and forth as opposed to having it move up and down. There are also subject differences in the centerstick tasks. EF seems to benefit more from the presence of the motion cues, as opposed to JK. To summarize, there is a moving-base improvement, but which direction the accelerations come in, longitudinally or vertically, appears to make little difference as far as the pilot opinion is concerned.

TABLE 4

PILOT COMMENTARY, SINGLE-AXIS TRACKING EXPERIMENT

CONFIG.	EF	JK
S LON VER	Lag is much more apparent in fixed base condition. Prefer moving base, but cannot see much difference between LON and VER.	Task less difficult with motion; tend to disregard motion. VER seems more real — get a pitching sensation, perhaps because I strain forward.
P LAT	Side-to-side movement is disturbing. Pedal task is more difficult to learn than stick task.	Motion is better with centerstick tasks. Rocking of my head screws up my lateral control. Task may be tougher with motion.

In the pedal tasks, both pilots are somewhat disturbed by the lateral motion and, further, the task is regarded as less real, or more difficult, than the centerstick task. JK comments that the lateral motion causes his head to move and therefore reduces his ability to fixate on the vertical needle. In short there is relatively little difference, fixed-base to moving-base; and the reason apparently is that the lateral motion itself is more disturbing or inhibiting than it is beneficial.

2. Tracking Performance

Next, consider the two subjects' performance, Fig. 2, as indicated by the standard deviation of the motion variable (λ) on the one hand and the measured Y_pY_c crossover frequency, ω_c, from the describing function analysis on the other. These results represent only the last two runs (three in the

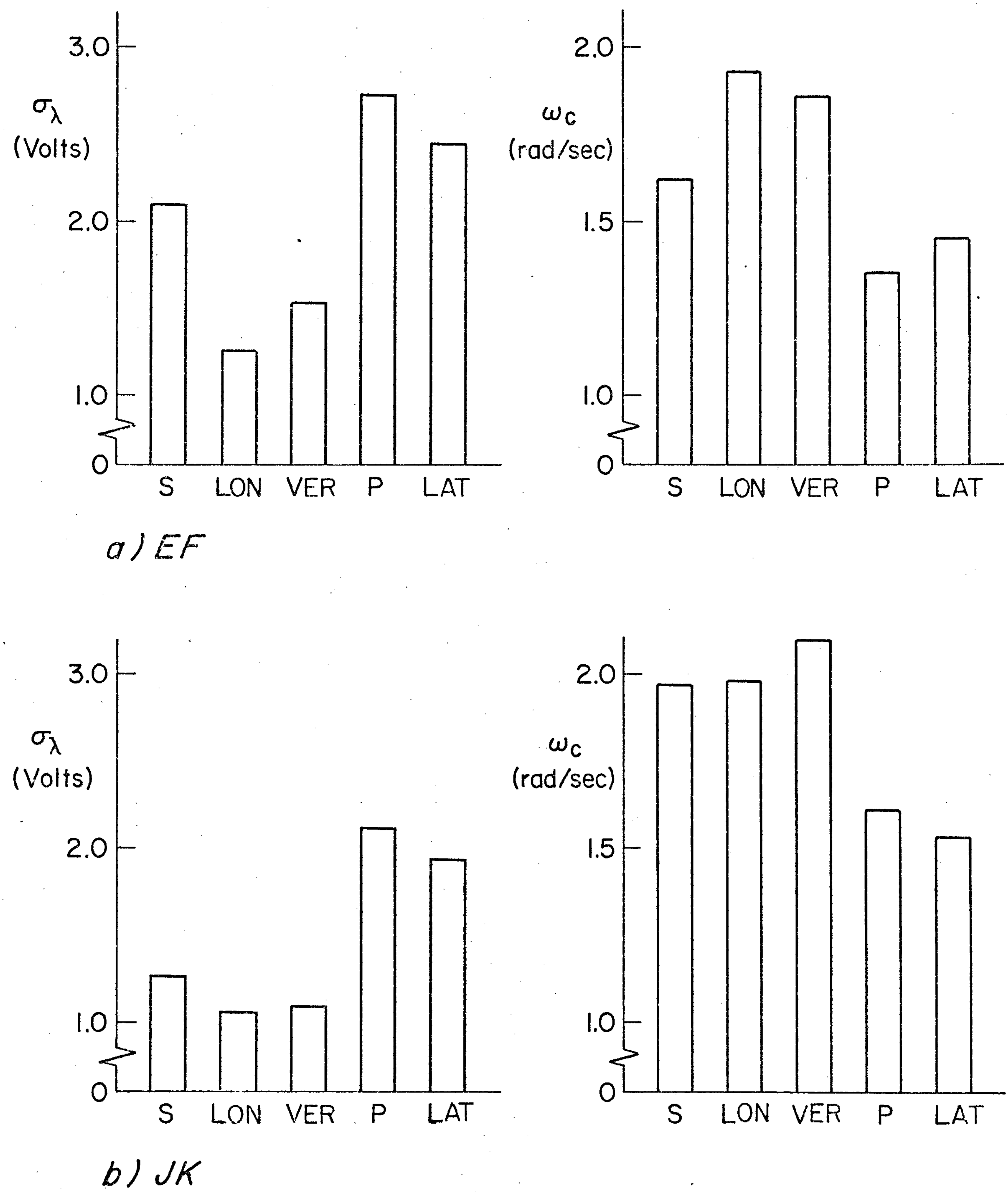


Figure 2. Averaged Tracking Performance and Crossover Frequency

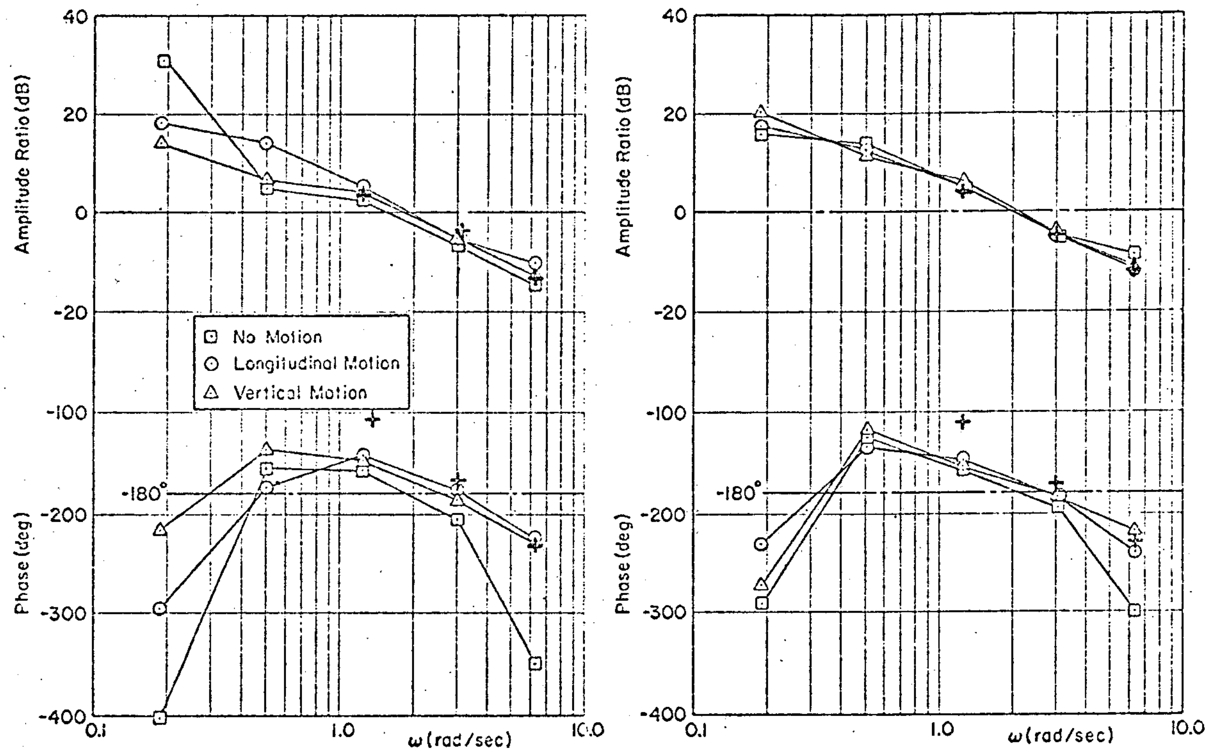
case of LON and LAT configurations) which were run at a higher gain, $K_c = 3.96$ cm/sec^2 (display) per cm (control deflection), and also represent a higher level of training. The data show, for EF in the centerstick task, that motion improves performance, as signified by the reduction of σ_λ and the increase in ω_c. This improvement is significant at better than the 1% level (F test for equality of variances). There is a relatively small difference between the longitudinal and vertical motion cases, which tends to confirm what the pilot had to say about the task. JK's performance was in general better than EF's, however he showed a lesser degree of improvement (significant at the 10% level), going from fixed base to moving base for the centerstick tasks.

Now consider the lateral task performance exhibited in this figure. Although there is an improvement in performance on the part of both pilots, the improvement is relatively small and no significance can be established. The crossover frequencies change a relatively small amount and, for JK, it goes <u>down</u> with motion, an apparent inconsistency since his performance improves. The explanation in this instance is that the coherence, as measured by the ratio between the correlated (with the disturbance, λ_d) and total power in the λ signal, is increased in the LAT configuration by an amount more than sufficient to offset the decreased bandwidth as indicated by ω_c.

3. Describing Functions

Perhaps the most important data from this experiment are the describing function results. Figure 3 illustrates these open-loop describing functions for the centerstick tasks. It is clear that the crossover model holds for these data as the gain characteristics show crossover at a slope of −20 dB/decade for both subjects. The task is difficult: gain margins vary between 2 and 6 dB; phase margins between 10 and 30 deg.

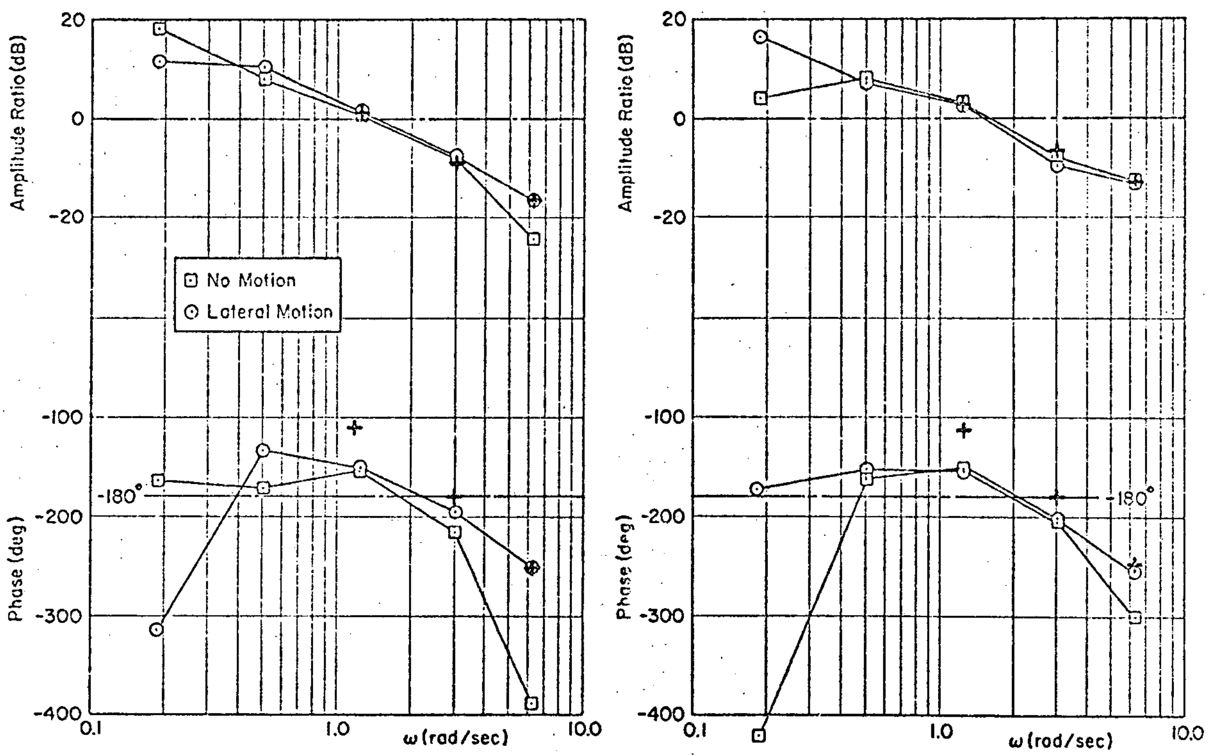
The most apparent differences between the fixed and moving base data are the reduction in high frequency (at 6.28 rad/sec) lag, moving base (by about 120 deg, EF; 60 to 80 deg, JK) and the improved gain and phase margins, moving base (by about 2.5 dB and 8 deg). The pilot's effective time delay has been significantly reduced in the moving base cases, and for EF there is



a) EF

b) JK

Figure 3. Describing Functions, Centerstick Task



a) EF

b) JK

Figure 4. Describing Functions, Pedal Task

a substantial improvement in crossover frequency as already noted in Fig. 2. On the other hand, there are only slight differences between the two moving base conditions for either subject.

Comparing subjects, Fig. 3 shows that EF gets more benefit out of the linear motion than does JK. However both subjects show closely comparable data moving base — the major difference between the two subjects lies in their fixed base data.

No firm conclusions can be drawn from the low frequency data, i.e., the lowest two frequencies in Fig. 3. The measurements at these frequencies were quite noisy because of the very low signal levels. The data points shown at the two lowest frequencies represent a grand average of all the runs for a particular subject and configuration, while the highest three data points represent only the last two or three runs.

The moving base data are not incompatible with current models (e.g., Ref. 8) of the dynamic response of the composite linear proprioception senses (lps) if it is assumed that these cues are dominant at high frequencies. A hypothesized high frequency model is then given by:*

$$Y_p Y_c \Big|_{fit} = \frac{K_p K_c}{s+1} Y_{lps} e^{-\tau s} \tag{2}$$

where $\tau = 0.2$ sec, K_p is adjusted for the best fit of the amplitude data for each subject, and Y_{lps} is based upon the data of Ref. 8. These data suggest a phase characteristic equivalent to first order lag with a break frequency, $1/T = 1.5$ rad/sec, and a gain characteristic which falls off at -6 dB/decade (i.e., $\omega^{-0.3}$). The resultant fit using the actual Ref. 8 data is shown by the + symbols in Fig. 3.

The data for the pedal tasks are shown in Fig. 4, and the same qualifying remarks concerning the two lowest frequencies apply. Here the fixed base versus moving base differences are substantially less than in Fig. 3. In particular, only the lag at the highest frequency shows a substantial improvement, moving base (by about 45 deg, JK; by almost 140 deg, EF!). Again, the intersubject differences are small in the moving base case. The crossover

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*The s^2 term in the controlled element is eliminated because the otoliths sense acceleration.

frequencies for these tasks are less than for the centerstick tasks while the gain and phase margins are comparable. This bears out the remarks concerning the inherent difficulty of the pedal task (Table 4). The + symbols in Fig. 4 represent a linear proprioception senses model fit as in Fig. 3, only here $\tau = 0.25$ sec.

4. Summary and Conclusions

There are four major results from the foregoing material (additional information concerning learning trends is contained in Appendix C). The first of these has to do with dominance of motion effects. Pilot commentary, performance, and measured describing functions all show a substantial improvement, moving base, in the centerstick tasks; less so in the pedal tasks. The major effect is to reduce the pilot's effective time delay — in this respect the data resemble results obtained in attitude control tasks (c.f., Ref. 1) when going from fixed to moving base.

Secondly, subject differences are important. EF is more relaxed, while JK is more intent. JK comments, for example, that his head bobs up and down in the VER configuration because he strains forward to see the display better. This difference in style is apparent in the better performance, increased crossover frequencies, and generally smaller gain and phase margins exhibited by JK relative to EF.

Thirdly, the data show that the effective acceleration thresholds in this task are relatively low. The root mean square acceleration ranges between 0.04 and 0.06 g. Since the pilots are using these signals effectively as indicated by the fixed base/moving base differences, the effective threshold lies near this level or lower. Physiological measurements of this threshold (c.f., Ref. 9) are around 0.01 g, vertically (in a 1 g field) and somewhat less when measured longitudinally or laterally. The result is therefore compatible with these physiological measures.

Finally, the data indicate no substantial difference due to the direction of the acceleration in the pilot's ability to respond to this cue in a tracking task. Certainly no substantial vertical/longitudinal differences are indicated even though bobweight effects plus a presumed lower acceleration threshold, longitudinally, could contribute to improved performance in the LON configuration relative to VER. Such differences which do exist (see EF's data in Fig. 3) are substantially less than motion versus no motion.

No comparison can be made with the lateral direction. Substantial differences in task (primarily in using pedals), the lack of lateral restraint, and (suggested by pilot commentary) extraneous lateral accelerations may all contribute to the relatively small (and statistically insignificant) performance improvements, fixed to moving base. The pilots both note some differences in the lateral acceleration sensation as a function of cab position on the tower, suggesting the presence of "noise" in the acceleration "signal" when moving laterally.

There are three major conclusions to be drawn from these data:

- Low level linear acceleration cues can be effectively used by pilots to improve performance in tracking tasks.
- Pilot sensitivity to these cues is approximately the same for the fore-and-aft and vertical directions.
- Pilots may vary greatly in their ability to utilize the linear motion cues.

The first of these is significant because in the past there have been doubts as to the utility of purely linear motion cues in continuous tracking tasks. The results here are unambiguous. The second conclusion is qualified by the magnitude of the linear accelerations used in this experiment — the rms levels are roughly five times as large as physiological measurements of linear acceleration threshold. The result is therefore not unexpected. At lower levels of acceleration, one would expect the overall benefits of motion to be lessened and the directional differences (if any) to be relatively increased. The final conclusion is to be expected on the basis of past experimentation with motion cues by a number of investigators.

SECTION III

IFR TRACKING EXPERIMENT

A. EXPERIMENT DESCRIPTION

As indicated in the Introduction, Section I, the primary purpose of this experiment was to shed some light on questions raised by the Phase I experimental results. These results are summarized in Section I and described in more detail in Appendix B. Briefly, the questions are as follows:

- Do inhibition or distraction effects associated primarily with the lateral similator motion have a detrimental effect on pilot-vehicle performance?
- Is display sensitivity (specifically, the ILS) an important factor in the measured pilot-vehicle performance?

The first question was raised by the observation that motion tended to deteriorate performance. This, coupled with pilot commentary concerning the simulator motion and concern with hitting the motion limits suggested that the experimental situation was such that motion did more harm than good. The second question refers to the fact that the ILS needle velocities are so low as to preclude the pilot's direct perception of needle rate.

Five experimental configurations were used in the IFR tracking experiment to answer these questions. These are listed in Table 5. The first two were intended to repeat the Phase I experiment, thereby providing a basis of comparison for the effects of the remaining three configurations. (There were some small changes from Phase I; specifically, the slip indicator sensitivity was increased and the rudder pedal forces decreased — both in response to pilot complaints during Phase I.) The last three configurations were meant to reveal the effects of needle sensitivity, inhibition or distraction caused by lateral motion, and the combined effect of both. In all cases, there was no lateral/directional stability augmentation system (SAS) in the simulated aircraft.

TABLE 5

CONFIGURATION SUMMARY, IFR TRACKING EXPERIMENT

SYMBOL	DEFINITION
FB	Fixed Base
MB	Moving Base
MB + N	Moving Base with ILS needle sensitivity doubled
MB − L	Moving Base with no Lateral ($\hat{\varphi}$, $\hat{\psi}$, and $\hat{y}$) motion
MB + N − L	Combination of the preceding two conditions

The pilot's task in this experiment was the same as in Phase I — to minimize glide slope and localizer errors while conducting an IFR approach. The situation was configured to allow measurement of time averaged (over 100 sec) means and variances of several motion variables, and of the pilot-vehicle describing function in the altitude control task.

The subject in this experiment was the same NASA research pilot who had participated in the Phase I experiment. He is a former USN pilot with some 1600 hrs in single engine jets. His 2000 hrs flight experience as a research pilot is primarily in single engine jet aircraft but also includes some jet transport and propeller driven time, the latter including the Twin Otter and Buffalo aircraft types. He has extensive simulator experience on a variety of moving base simulators at ARC.

The initial warmup and training runs were made with and without disturbances, and with and without the lateral/directional SAS. Following these, the protocol typically consisted of an hour-long session of ten runs (sometimes one or two more if data was lost for one reason or another) during which the subject was exposed to each of the five configurations twice. He was informed of the changes in each case prior to the run.

B. EXPERIMENTAL RESULTS

1. Tracking Performance

First, consider some of the performance data as represented by the standard deviation of glide slope error. This is plotted as a function of run number for each of the five configurations tested in Fig. 5. The asterisk next to the data point for Run 28 identifies an abnormally large error which is attributed to a malfunction in the input disturbance generator, i.e., the describing function analyzer (DFA). Disregarding this data point, it is clear that learning is taking place, especially for those configurations where the needle sensitivity was at its normal value (FB, MB, and MB – L).

Figure 6 shows similar data, in this instance, the localizer error. There is a large amount of scatter, particularly in the FB and MB cases. The asterisks by several of the data points refer to runs where the pilot noted that the attitude ball was sticking in yaw; however these comments do not correlate with localizer performance. There were a number of occasions when the pilot stated that the ball was sticking often enough that he wasn't going to mention it — it would have been too much of a distraction to verbalize.

Figures 5 and 6 provide a good indication of the data scatter in the experimental results. There are several contributing factors. First, there is a definite learning trend in the glide slope data (Fig. 5). A second factor is a defect in the experimental setup — a faulty attitude ball (Fig. 6). The lateral data is too variable for conclusive results and will not be considered any further except to note that task difficulties here (in the lateral task) probably contribute to the variability in the measured longitudinal task performance.

A third factor contributing to the data scatter is the generally low signal-to-noise ratio is the altitude control task. The describing function measurements (to be discussed below) indicate low coherence, i.e., less than a third of the error (in this case, the altitude error) power is correlated with the known and fixed input disturbance. Thus many runs (data points) at an asymptotic level on the learning curve are needed to establish significance in the effects observed.

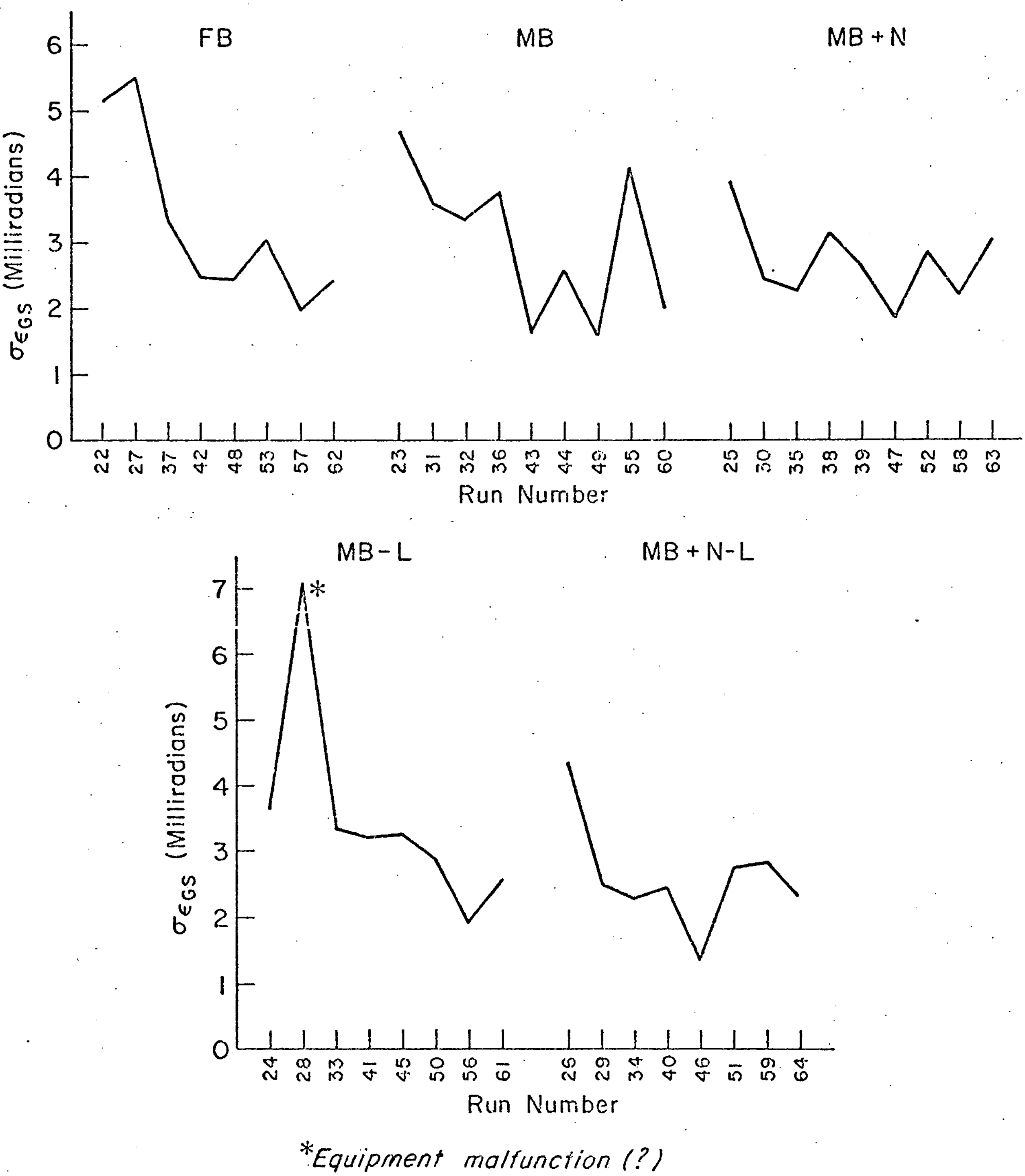

Figure 5. Glide Slope Performance Data, IFR Tracking Experiment

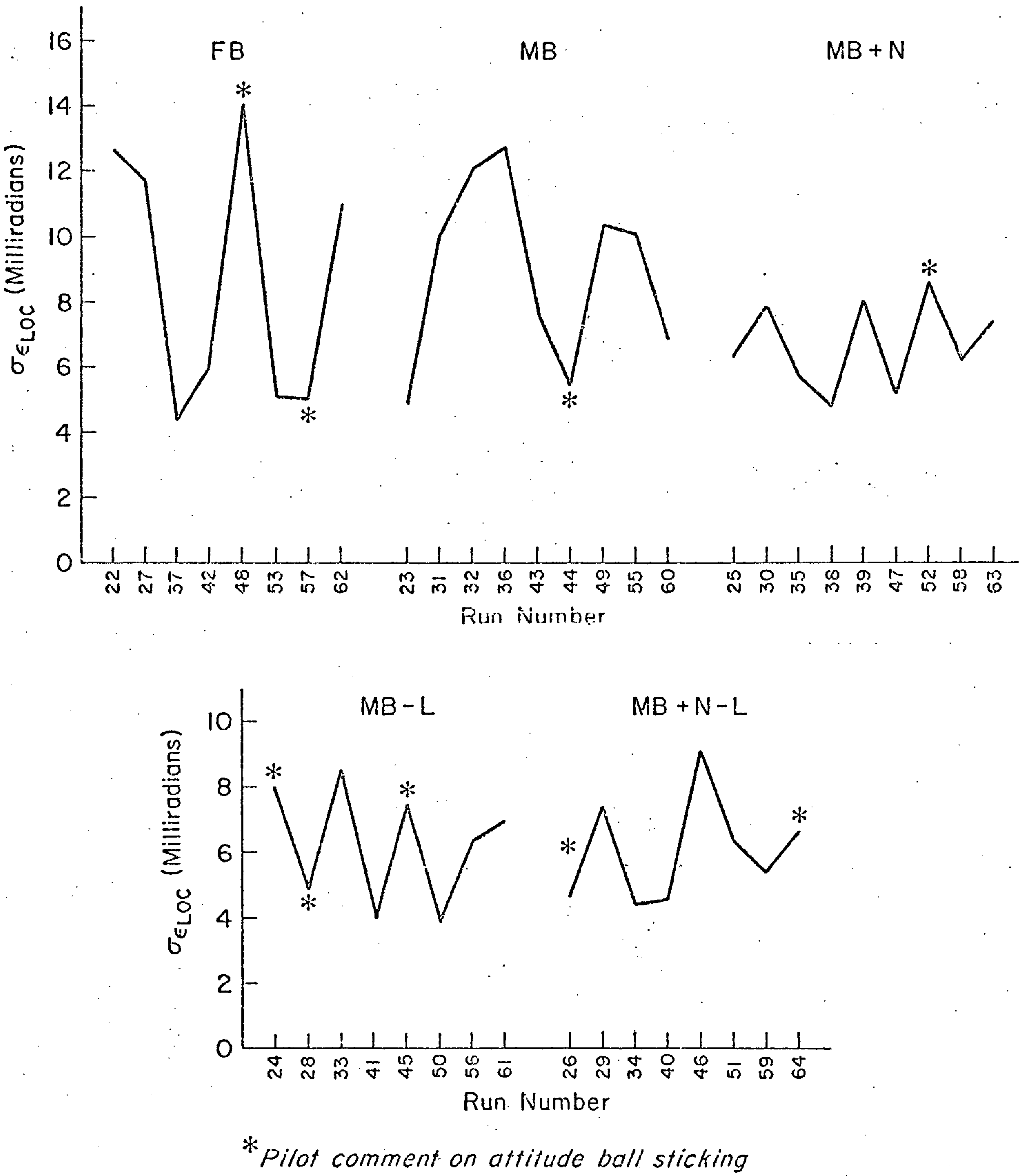

Figure 6. Localizer Performance Data, IFR Tracking Experiment

2. Describing Functions

The describing function results form the next body of data to be considered. The describing function measured was $Y_{p_h}Y_c$, that is, the pilot-vehicle describing function in the altitude control task. Y_c is the effective altitude response of the AWJSRA with the inner attitude and airspeed loops closed by the pilot. The method of making these measurements is discussed in Appendix A and schematically indicated in Fig. A-9.

The describing function data are valid only for the last four runs for each of the Table 5 configurations. The earlier data are disregarded because of a malfunction in the DFA which was identified and corrected only for these last several runs.

The run-by-run describing function measurements for each configuration were subject to much the same scatter as the corresponding performance data. For example, the apparent gain in the region near crossover varied over a range of 3 to 18 dB, typically about 8 dB — a little more at the lowest measurement frequency (ω = 0.1886 rad/sec) and somewhat less at the next two higher frequencies (ω = 0.503, 1.257 rad/sec). The range of gain data was somewhat larger for the FB and MB cases. The phase data in this frequency region were also highly variable. Here the range was 15 to 170 deg, typically about 60 deg. The phase data range was smallest for the configurations with increased needle sensitivity (MB + N and MB + N − L).

In view of the foregoing, it can be appreciated that the averaged (treating the four runs for each configuration as one long run) describing function data shown in Fig. 7 and listed in Table 6 for each of the five experimental configurations are subject to considerable uncertainty. Nevertheless, the dominant trends in these data are judged to be valid. The top row shows the ratio between $\sigma_{\dot{h}}$ and σ_h. This ratio approximates the bandwidth in the altitude control task and is determined from the averaged (over the last four runs) performance measures. It is shown with the describing function data because it adds a confirming note to the measured value of the crossover frequency, ω_c, which is interpolated from a scatter of data points. In particular, for the MB case, there is one wild point which renders it difficult to establish what the crossover

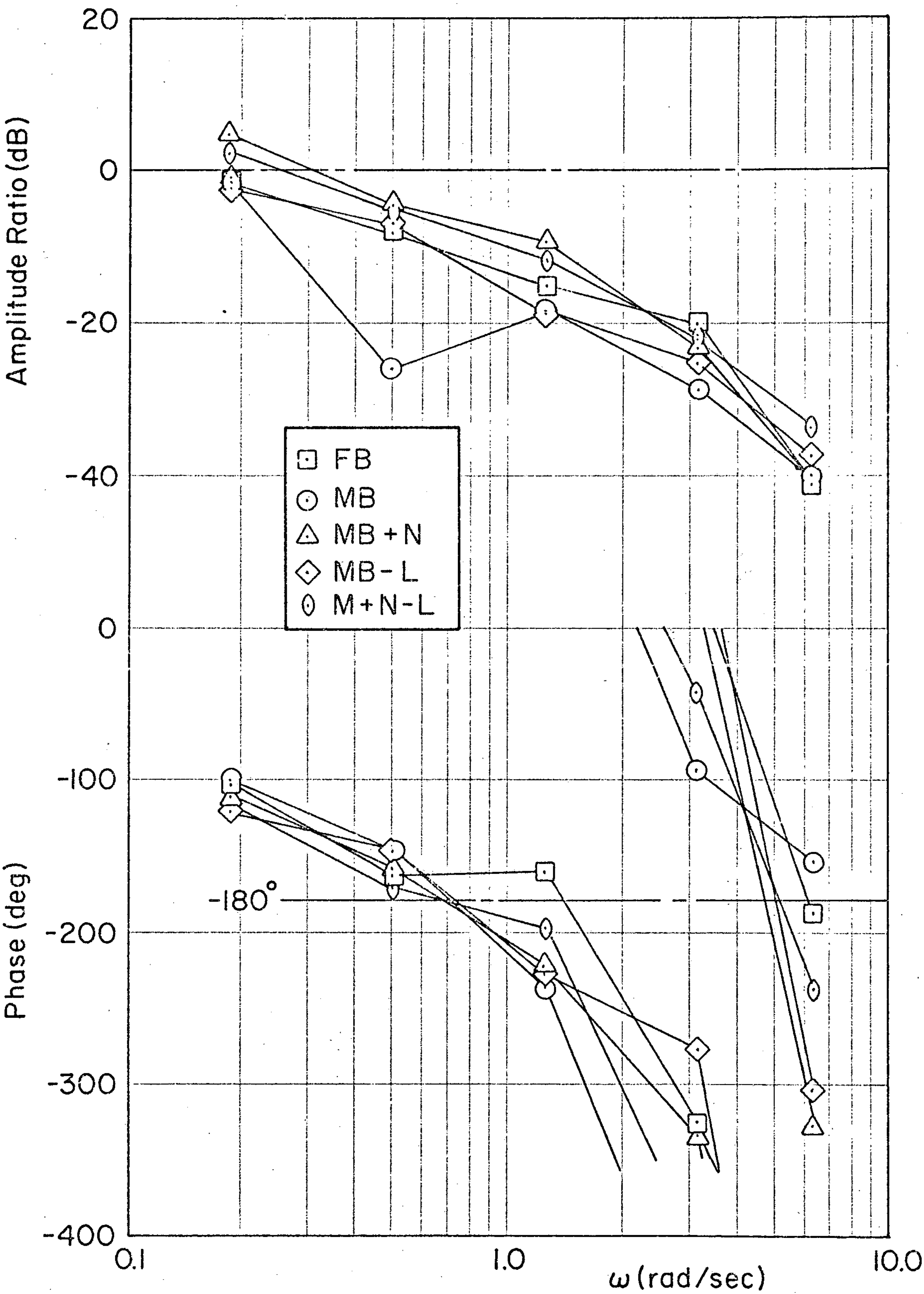

Figure 7. Describing Functions, VFR Tracking Experiment

TABLE 6

AVERAGED DESCRIBING FUNCTION DATA,
IFR TRACKING EXPERIMENT

PARAMETER		CONFIGURATION				
SYMBOL	UNITS	FB	MB	MB + N	MB − L	MB + N − L
$\sigma_{\dot{h}}/\sigma_h$	sec^{-1}	0.230	0.199	0.278	0.206	0.299
ω_c	sec^{-1}	0.16	0.16	0.30	0.13	0.25
k_m	dB	15	12	7	11	8
φ_m	deg	90	90	50	70	50
ρ^2	—	0.230	0.137	0.198	0.248	0.302

frequency is from the measured describing function. The first two rows of data, that is, $\sigma_{\dot{h}}/\sigma_h$ and ω_c are in reasonable correspondence and show very interesting changes in going from one configuration to the next.

The crossover frequency is largest for those cases where the needle sensitivity has been increased, i.e., in the MB + N and MB + N − L cases. The remaining cases (FB, MB, and MB − L) all show lower crossover frequencies. When the needle sensitivity is at its normal value, the crossover frequency is between 0.13 and 0.16 rad/sec. At high needle sensitivity, the crossover frequency ranges between 0.25 and 0.30 rad/sec. Along with these changes there are equivalent changes in the measured gain and phase margins (k_m and φ_m). For cases with increased needle sensitivity, there are lower gain and phase margins. The pilot-vehicle gain has gone up by 4 to 5 dB in the region of crossover. This compares with the 6 dB increase in the needle sensitivity.

The gain increase is in contrast to the more usual experience in instances where the display or controller sensitivity is changed and the pilot vehicle gain typically remains unchanged. The gain increasing in the present instance suggests the operation of a threshold-like effect in the pilot.

The pilot did not like the increased gain situation. The data show that his control activity increased while his altitude performance tended to improve only slightly — his display (ILS) motion amplitude therefore increased. The pilot works harder but it doesn't reduce the error that he sees, so his opinion deteriorates.

The last row of figures in Table 6 is the measured value of ρ^2, the ratio between that amount of output (altitude) power which is correlated with the input disturbance and the total output power. It indicates how closely related the output signal is to the disturbance. Lower correlation (smaller ρ^2) indicates a greater percentage of pilot remnant or noise from other sources in the signal. It also implies a greater degree of uncertainty in the measured describing function because the measurement technique cannot distinguish between signal and noise at the measurement frequencies. Where ρ^2 is relatively large, the remnant (or noise) is considerably less and the measured describing functions are subject to less measurement error. Using ρ^2 as a figure of merit in comparing configurations is strictly valid only where the task dynamics are the same, i.e., where the crossover frequencies are substantially the same. Clearly, the data of Table 6 show the remnant to be significant — ρ^2 is quite low for all configurations.

The Table 6 data show the crossover frequencies to be relatively high for the MB + N and MB + N − L cases. But the ρ^2 in the second instance is 50% greater than the first. Since the performance is approximately constant, this difference implies somewhat improved task dynamics for MB + N (reasonable, since the presence of lateral motion, a stabilizing influence on the lateral control task, would be expected to allow the pilot to concentrate more on the longitudinal task) with increased remnant. A similar result holds when comparing the low ω_c cases, MB and MB − L; the ρ^2 in the latter case is 80% greater than the former. The ρ^2 in the FB configuration is almost 70% greater than in MB. The common factor tying all these examples together is a larger proportion of remnant where lateral motion cues are present, lower otherwise. In short, the inhibition/distraction effects of the lateral motion about cancel the beneficial effects of its presence — the performance is essentially unchanged. This is borne out by the pilot's remarks to the effect that there is "little difference" in the moving base cases between the presence or absence of the lateral motion cues. And this is in a situation where motion cues could help because of the unstable roll task dynamics (a divergent spiral mode) without SAS.

3. Summary and Conclusions

Perhaps the most important result of the experiment is a negative one, that is, that motion effects are relatively minor, at least on the longitudinal control task. In comparing the results for FB with MB – L (only longitudinal cues are added) or with MB (all motion present) we note minor and inconsistent performance changes. There is a tendency for the pitch attitude control "bandwidth," σ_q/σ_θ, to decrease with motion and the pilot feels that FB is, "perhaps a little harder to fly," than MB. (Appendix C identifies the trends exhibited by the performance data noted here.)

Secondly, the data clearly show that increased ILS needle sensitivity dominates the results. In particular, the pilot's control activity and pitch rates increase and his altitude errors decrease. The describing function data show larger crossover frequencies and a tendency for decreased remnant. The pilot notes a difference in task difficulty, feeling that the vehicle is, "harder to fly, particularly in the lateral task," and for reasons noted earlier — larger apparent (displayed) errors and greater stick activity.

Thirdly, the data show that the lateral motion is distracting or inhibiting. When lateral motion is removed, there are only slight performance improvements and the pilot sees, "little difference," between the conditions. But the remnant or noise in the longitudinal task decreases. Overall, the results suggest that the benefits of lateral motion ($\hat{\varphi}$, $\hat{\psi}$, and $\hat{y}$ degrees of simulator freedom) are balanced by the inhibition/distraction effects. If these effects weren't present, it is possible that the presence of lateral motion cues could result in improved performance over that exhibited here.

There are two major conclusions to be drawn from the results of the IFR tracking experiment:

- Motion cues primarily affected attitude control and had relatively little influence on path performance.

- Display scaling effects were of greater importance than motion effects with regard to path performance.

The first is in accord with pre-experimental predictions for the AWJSRA (Table B-2), while the second directly answers one of the questions raised by the results of the Phase I experimentation.

As noted earlier, a strong case can be made for the presence of "inhibition/distraction" effects (as described in the Introduction on page 5) in the data obtained. This argument is based primarily upon measures of error signal coherence (correlation with the input disturbance) obtained from describing function measurements. However, the low coherence and the small number of measurements coupled with a relatively low measurement accuracy suggest caution in drawing this conclusion. If valid, there are important implications with regard to the results obtainable from motion simulation. The data suggest that motion benefits can be negated by these effects, leading to erroneous conclusions regarding the benefits of motion cues. The present experiment is not exempted from this reservation.

SECTION IV

VFR TRACKING EXPERIMENT

A. EXPERIMENT DESCRIPTION

The basic purpose of this experiment was, broadly speaking, to determine the effects of motion cues in a simulated VFR task. Its specific objectives were identical with those of the program as a whole (see Section I).

In configuring the experiment, there was little experience from the Phase I experiment to draw upon. The task selection was motivated, in part, by the desire for a situation where the anticipated results could be obtained within the scheduled test period. This criterion eliminated experimental situations requiring a great many repeat runs to establish data trends. Specifically, a flare-to-touchdown task (i.e., the VFR portion of the Phase I experiment) was felt inappropriate because of the need for many runs to establish a basis for performance comparison. This would have been a time-varying task so only ensemble-averaging and not time-averaging could have been used. With a stationary task one can time average and therefore obtain results with many fewer runs.

The task selected was that of low altitude, level flight above and along a long runway in the presence of light turbulence. The aircraft was the AWJSRA trimmed out for level flight at 30.5 m/sec and operating with the lateral and directional SAS on. The simulation setup is described in Appendix A.

Seven configurations of this task were flown as noted in Table 7. These were oriented toward specific objectives, as follows: First, to determine the general effects of motion, a fixed base (FB) and a nominal moving base (2) configuration were included. Second, to define tradeoffs in configuring coordinated washout configurations, a spectrum of such washouts was included (Configurations 1, 2, 3, and 4). These are all characterized by scale factors applied to the magnitudes of the computed accelerations and vehicle rates, and washout break frequencies, which are chosen to maintain motion

TABLE 7

CONFIGURATION SUMMARY, VFR TRACKING EXPERIMENT

CONFIG.	LONGITUDINAL TASK (x, z, θ)		LATERAL TASK (y, ϕ, ψ)	
	SCALE FACTOR	BREAK FREQUENCY	SCALE FACTOR	BREAK FREQUENCY
FB	Fixed Base		Fixed Base	
1	0.5	0.35 rad/sec	0.35	0.35 rad/sec
2	1.0	0.50	0.50	0.50
3	1.0	0.75	0.75	0.75
4	1.0	1.0	1.0	1.0
2 (no $\ddot{z}$)	Same as 2 with no vertical drive to simulator			
2 (no $\ddot{x}$, θ)	Same as 2 with no pitch or longitudinal simulator drives			

within the linear travel limits of the simulator. In going from Configuration 1 to 4, one goes from attenuated motion with low residual tilt rates to full scale motion with large residual tilt rates.

Finally, the vertical and longitudinal cues were separately deleted from the nominal washout configuration to determine whether or not these cues contributed to the task. In the latter case, the pitch rate cues were also deleted to remove the residual tilt component of the sensed longitudinal accelerations.

The subjects in this experiment were the same two who participated in the single-axis tracking experiment (Section II). After a lengthy training period to establish a stable performance level, the protocol called for exposure to the seven configurations in random order (and unidentified to the subjects except for FB) in experimental sessions generally lasting an hour or more (14 runs). The metrics were the same as in the IFR tracking experiment: pilot commentary, measured performance (means and variances of several motion variables) and describing functions in the altitude control task.

B. EXPERIMENTAL RESULTS

The performance, as measured by the variances in altitude, h, and lineup (or lateral deviation from the runway centerline), y, for the two subjects for the fixed base (FB) and nominal moving base (2) configurations, serves as an introduction to the nature of the data obtained. The run-by-run performances for the last six runs in each instance is illustrated in Fig. 8 — this represents a well trained situation where the subjects should be close to an asymptotic, well-trained performance level.

Considering the level of training, there is considerable scatter exhibited in these data, somewhat more for EF than for JK; and perhaps somewhat more for Configuration No. 2 than FB. The subject commented on a "jerky" visual display on run 212 which may have contributed to poor lineup performance; but for run 272 there is no ready explanation.

Figure 8 also shows that the fixed base-moving base differences are relatively small with the differences perhaps being a little greater for lineup — the errors decrease slightly for the moving base situation.

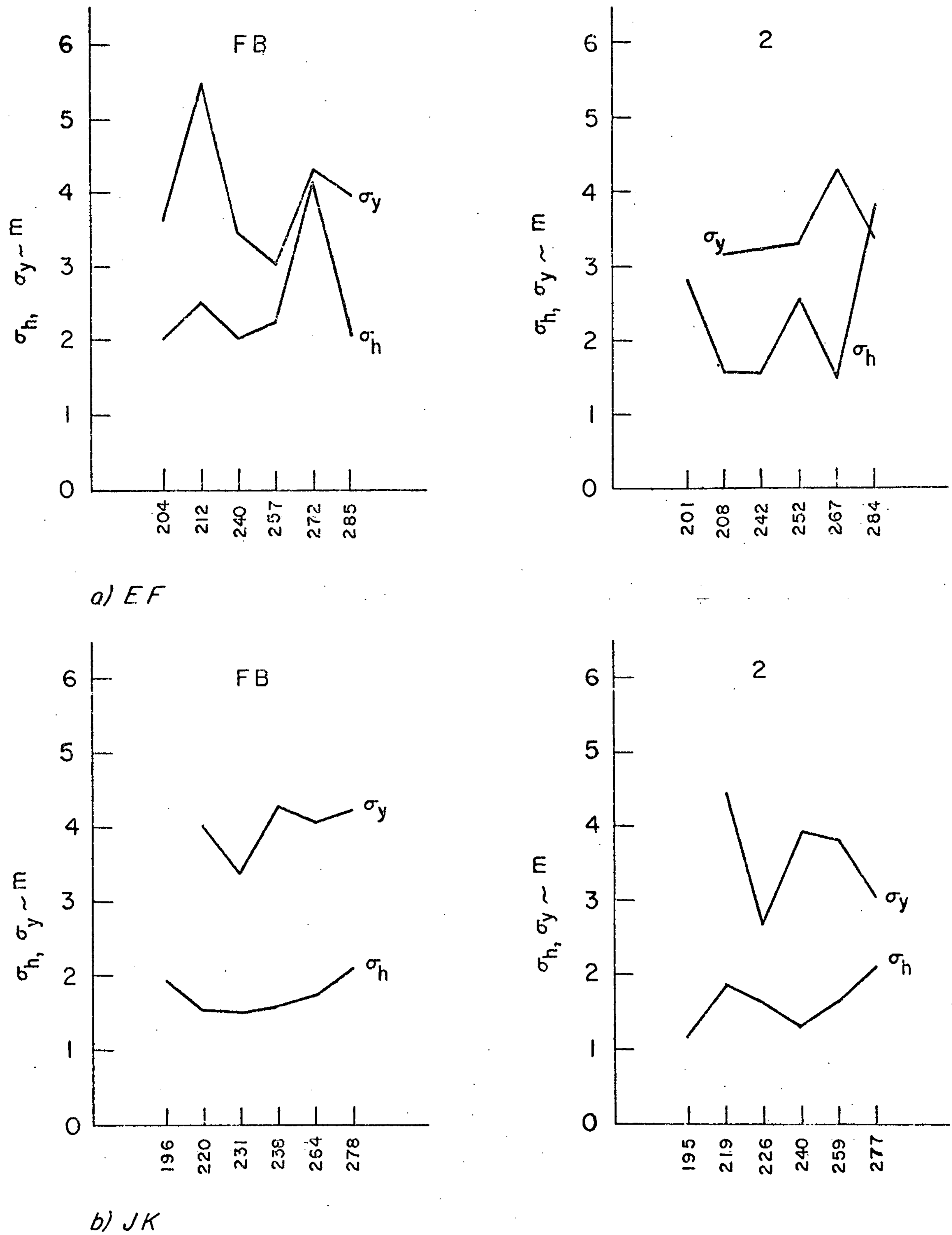

Figure 8. Performance Data, VFR Tracking Experiment

Subject differences also show up with JK's altitude performance being better than EF's. Overall, the example data of Fig. 8 suggest an experimental situation wherein configuration differences are small and the measurements noisy, that is, subject to considerable scatter.

1. Pilot Commentary and Opinion

The example of Fig. 8 suggests that attention be focussed elsewhere in trying to assess differences among the seven configurations used in this experiment. Table 8 presents a compilation of the pertinent commentary as a function of configuration and subject. In the fixed base configuration the pilots apparently miss the lateral cues in that they have a tendency to overcontrol; they feel that the task is somewhat more difficult without the motion cues. The next configuration listed is the so-called base line, or nominal moving base configuration, No. 2. This was quite similar to the configuration used in the IFR tracking experiment, where the longitudinal scale factor was 0.5 instead of 1.0. The comment is that the configuration is more realistic than Configurations 3 or 4, but that there is some jerkiness and rumble in the simulator. The reason for their noting the simulator jerkiness and rumble is probably because the magnitude of simulator motion in the longitudinal and vertical directions is greater for this configuration than for any of the others.

The next configuration listed in Table 8 is the base line configuration, No. 2, without any vertical acceleration cues. Here EF says that the motion is artificial and that altitude control is more difficult. However he is not able to identify the fact that the vertical motion is missing. On the other hand, JK says that, "I have a smoother ride," the implication being that he actually likes this configuration a little bit better than No. 2. With the fourth configuration on the list, Configuration No. 2 without any pitch cue or longitudinal acceleration, EF states that the configuration is similar to No. 2 but slightly easier to fly, and it had better motion and a good pitch response. The only plausible explanation for this comment is that rather than have a limited amount of pitch rate cue and along with it a false residual tilt cue, he would rather be entirely fixed base with respect to these cues. The interpretation is that he is disturbed by the

TABLE 8

PILOT COMMENTARY, VFR TRACKING EXPERIMENT

CONFIGURATION	EF	JK
FB	Stable and easy to control with low level of disturbances. Have a tendency to overcontrol in roll.	Have a tendency to over-control, especially laterally. Prefer moving base — lateral task more difficult without motion.
2	More realistic than 3 or 4 with less movement (except vertically). Notice simulator jerkiness and rumble.	Less lateral motion than 3 or 4. Feels jerky — has some vibration and shudder. Like pitch response to diverter — hanging in straps.
2 (no $\ddot{z}$)	Motion feels artificial relative to 2 but with similar jerkiness. Altitude control more difficult.	Motion feels slightly attenuated relative to 2 with smoother ride.
2 (no θ, $\ddot{x}$)	Similar to 2 but slightly easier to fly — has better motion and good pitch response.	Very poor motion, almost like fixed base — has no pitch response to diverter, and I lose feel for diverter corrections.
1	Less lateral response, minimal vertical disturbance and a tendency to balloon, but relatively easy to fly. Poor pitch and $\ddot{z}$ cues.	Less motion than I like, particularly pitch response to diverter. More difficult to fly than 2.
3	Exaggerated pitch response to diverter changes and more responsive laterally. Motion is more realistic than 4.	Like this configuration, especially pitch response to diverter changes. Best motion and control response of all configurations.
4	Angular cues are confusing and unreal. Seems less stable in all axes — lurches and is jerky in response to both gusts and control inputs.	Has good pitch response to diverter but is unrealistic. Lateral motion is a hindrance and a distraction. Motion seems abrupt.

residual tilt. By contrast, JK misses the residual tilt cue and the pitch motion, and says that he loses his feel for diverter corrections. In effect, he misses the longitudinal sensations of acceleration which he would otherwise get and complains strongly about it. In the other moving base configurations he continually refers (favorably or otherwise) to the response of the simulator to the diverter corrections.

The fifth configuration listed is Configuration No. 1. Here both pilots make comments which suggest that there is less motion sensation than they would prefer. This is reasonable, as this configuration has the motion scale factors set at their lowest levels. However, EF says it is relatively easy to fly. JK complains about not having sufficient response to the diverter. For Configurations 3 and 4, there is considerable residual tilt to judge by the comments. The first pilot, EF, dislikes this quite a bit, but the second pilot, JK, rather enjoys it (at least for Configuration No. 3). JK thinks No. 3 is best of all. However, even he objects to the unreal pitch motion cues when they get large enough, as indicated by his comment on Configuration No. 4.

In an attempt to quantify this commentary, a brief sub-experiment was conducted in which the two subject pilots were asked to rate the seven configurations on an arbitrary scale. The methodology was as follows: A form was prepared whereon they were instructed to rate the seven configurations on an arbitrary scale from 1 (best) to 10 (worst) on two bases of judgment; first, performance and second, feel or realism. Here it was thought that there might be a difference between the two ratings — even though the cues are unrealistic, the subjects might be able to use them to improve their performance. The configurations were presented to them in random order except that No. 2 was first and FB last; and they were not identified to the subject. They were allowed to have repeat runs at their discretion to crystalize their impressions. JK took more advantage of this, asking for repeats on No. 2 to assist him in "calibrating" his ratings.

The results of this brief experiment are shown in Fig. 9. For JK the results correlate closely with his earlier commentary. In particular, the chart on the bottom left shows that he regards Configuration No. 3 as being optimum relative to the other motion configurations. The chart on the lower

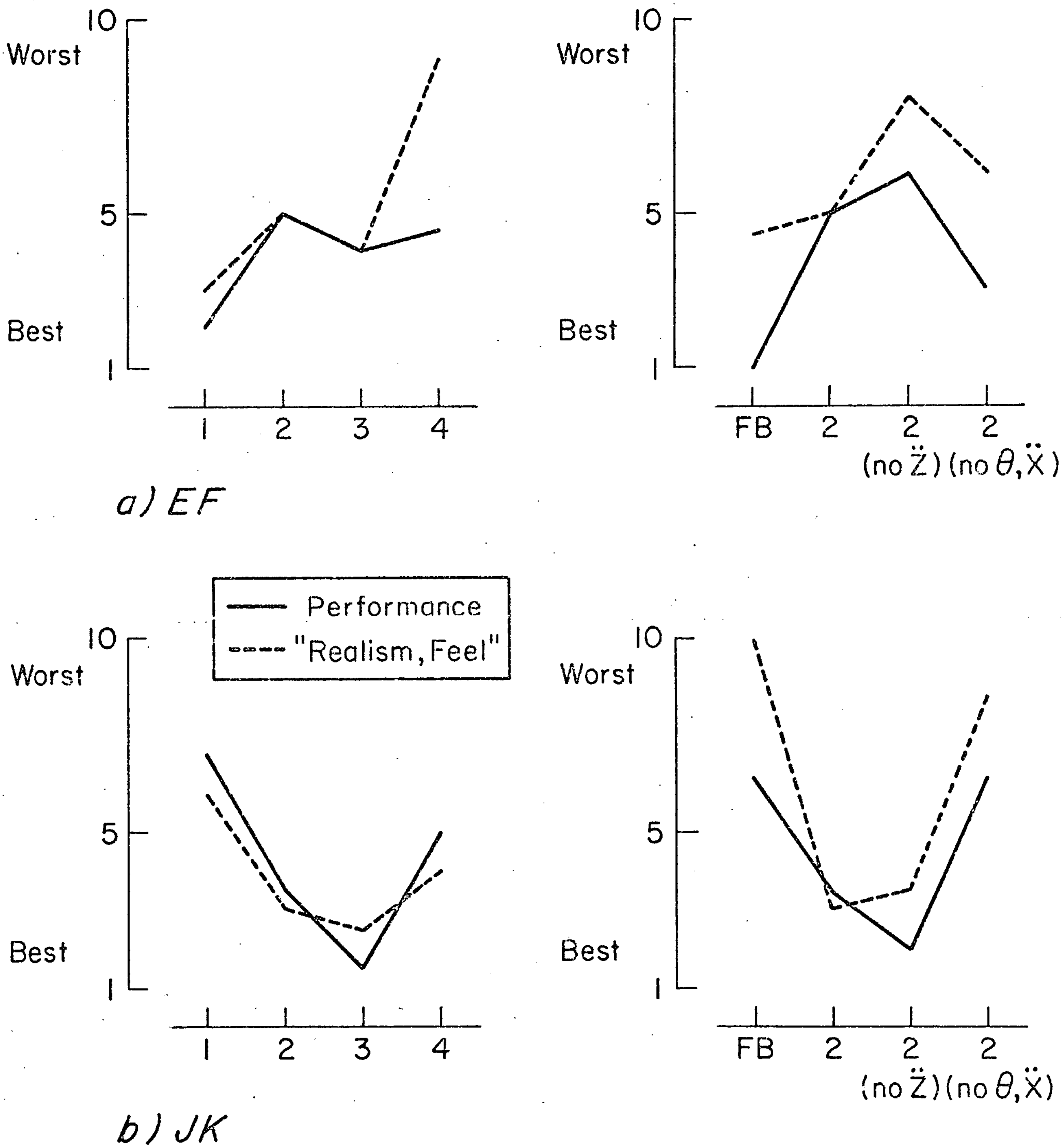

Figure 9. Pilot Opinion, VFR Tracking Experiment

right suggests a considerable deterioration for fixed base (FB) and a similar deterioration when the longitudinal acceleration cues are removed. However, for EF in the top set of charts there appears to be little correlation with his commentary. For example, the major thing to note from the left hand chart is that there is a considerable deterioration in the realism or feel for Configuration No. 4. The rating for No. 1 may correlate with his comment, "easy to fly." No. 2 suffers from vibration. But No. 3 earned poor remarks (Table 7) because of residual tilt — in Fig. 10 it appears to be better than No. 2. In this particular chart there isn't a strong correlation between his quantitative opinion and his commentary. For the chart on the upper right, the correlation is a little better. There is a considerable improvement, FB, which is not directly suggested by his commentary and certainly runs at variance with what might be expected or demonstrated — see Fig. 8. However, there is a deterioration in his opinion when vertical motion is removed. Further, the improvement in his performance rating, going from Configuration No. 2 to Configuration No. 2 without any longitudinal or pitch motion cues may be correlated with the fact that the latter configuration has no residual tilt cue.

Figure 9 and Table 8 suggest that there are considerable differences between the subjects. Some of these are listed in Table 9.

TABLE 9

SUBJECT DIFFERENCES, VFR TRACKING EXPERIMENT

EF	JK
1. Former USMC helicopter pilot.	1. Former USN fighter pilot.
2. "Relaxed" flyer and more run-to-run variation in performance. Somewhat poorer performance.	2. "Intense" pilot — says he strains forward to look at instruments.
3. Rarely uses pedal.	3. Uses pedals for heading control.
4. Typically flies about 1.5 kt fast.	4. Typically flies about 3 kt fast.
5. Claims to fly $u, \theta \rightarrow \delta_c$, $h \rightarrow \nu$.	5. No comment on technique.
6. Uses vertical acceleration cue (?)	6. Uses longitudinal acceleration cue (?)

First of all, one pilot is a former helicopter pilot, the other a former conventional aircraft pilot. There are differences in their flying styles and a common tendency to fly a little bit fast, thereby tending to improve the altitude responses of the aircraft. A significant comment is EF's claim to fly both airspeed (u) and attitude (θ) to the column (δ_c) and altitude (h) to the diverter (ν). This is a typical helicopter technique. The last statement in Table 9 refers to the suggestion that EF uses the vertical acceleration cue. This is correlated with sensations that are familiar to a helicopter pilot. EF uses the diverter and gets a vertical acceleration from it, at least eventually — this correlates with collective usage in a helicopter. On the other hand, for a Navy jet pilot, there are very few things more comforting than a substantial increase in longitudinal acceleration when the throttles are moved to the firewall. This is analogous to the situation with the AWJSRA. When the thrust diverters are moved, there is a substantial change in the longitudinal acceleration of the airplane for the flight condition being flown. When this cue is removed, JK does not like it; when present, he does like it, even though he gets some distorted pitch cues to go along with it. To summarize, one subject is a helicopter pilot, the other a conventional airplane pilot; the helicopter pilot tends to prefer helicopter cues, that is, vertical motions in response to the "anxillary" control (the thrust diverter); the conventional aircraft pilot tends to prefer the longitudinal acceleration response to the diverter — similar, in his words, to the response obtained with a flap control.

2. Performance and Describing Function Data

Past experience, e.g., the Phase I results, would suggest that motion differences will be most evident in the performance data pertinent to the attitude control task. For example, consider the averaged attitude rate data of Fig. 10. These data pertain to the last several runs (see Appendix C for a data listing) and no attempt has been made to edit the data (for example, Runs 212 and 272, suspect points in Fig. 9, are included).

The data in the two left hand charts would suggest that within the spectrum of washout configurations, No. 2 is optimum in some sense — the standard deviations of both yaw and roll rates are at minimums. The pitch

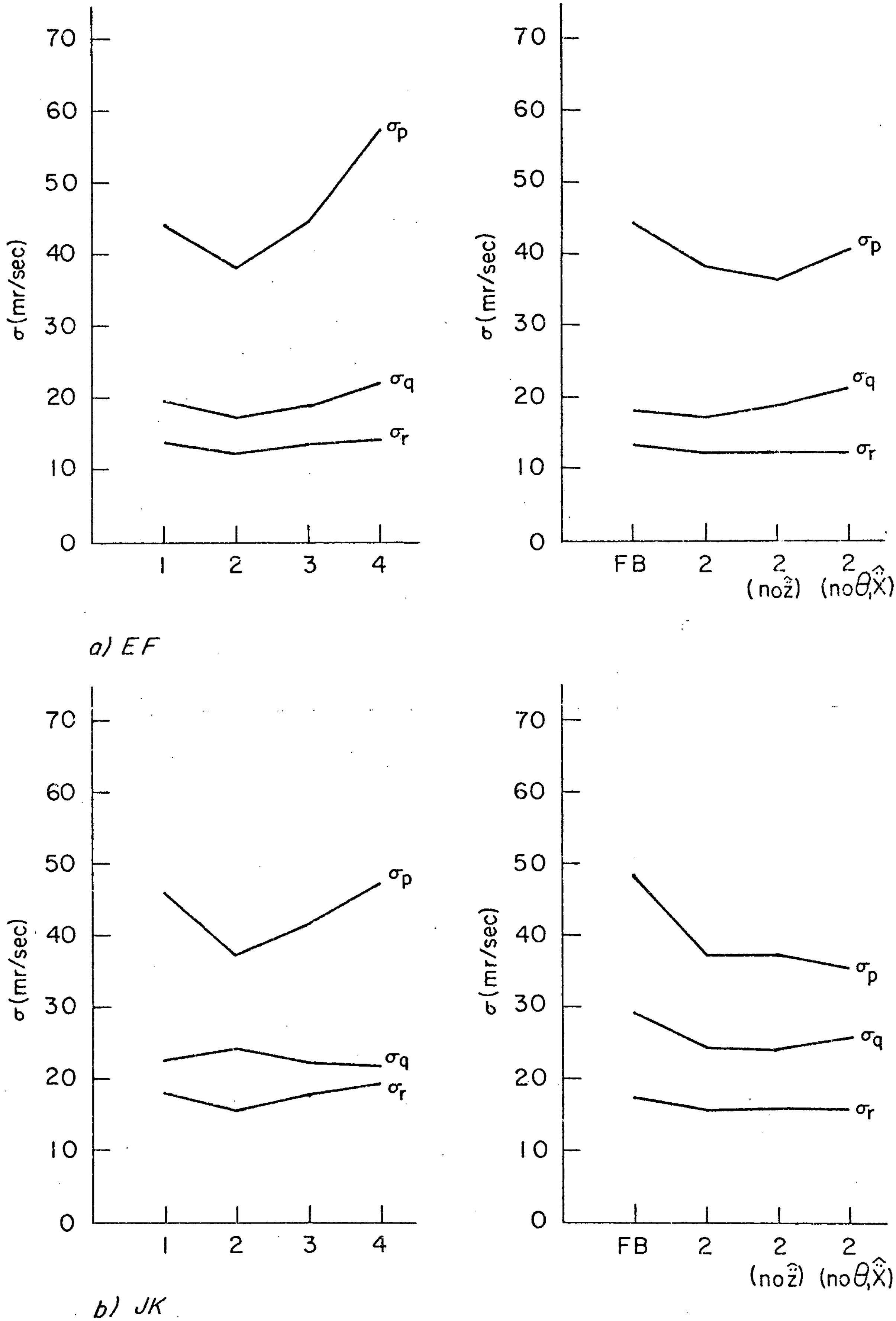

Figure 10. Averaged Attitude Rates, VFR Tracking Experiment

rates are at a minimum for EF, a maximum for JK, perhaps a further indication of style differences. Considering the right hand charts, the data show the moving base condition to result in a reduction in the attitude rates for both subjects; however, removing the vertical or longitudinal cue has a relatively small effect.

The data of Fig. 11 present a more clouded picture, particularly when considering the scatter in the data making up the averages. Thus, for EF, the upper left hand chart in Fig. 11 suggests optimum performance for Configuration No. 2 or No. 3 — a picture which would be altered if certain "wild points" were deleted. For JK, whose performance tends to be more consistent, the data do not suggest any clear-cut optimum. In the right hand charts, however, even edited data show a performance decrement in σ_h for EF when the vertical acceleration cue is removed — his altitude performance with this configuration was consistently below the average for all configurations. For JK, the small performance decrement in σ_h shown for the case where longitudinal acceleration (and pitch rate) cues are removed tends to confirm his commentary.

Only small differences are exhibited in the describing function data. These data were measured in the same way as in the IFR experiment. Figure 12 compares fixed versus moving base altitude describing function data for the two subjects (a complete listing is given in Appendix C). Other than a slight reduction in the phase lag for the moving base case for EF, there is little to distinguish these data. The coherence (ρ^2) for these data is low, ranging between 0.15 and 0.4 for all configurations and both subjects. Remnant dominates the altitude error signal and degrades the measurement accuracy.

3. Summary and Conclusions

There are six significant results from this experiment. The first and most obvious result is that differences between subjects dominate the data. One subject, EF, apparently uses a vertical acceleration cue, to judge by both his commentary and performance. He is also relatively sensitive to the anomolous rates resulting from residual tilt terms in the washout scheme used. The other subject, JK, may use longitudinal acceleration cues — at least he is vocal about them — and is relatively more tolerant of residual

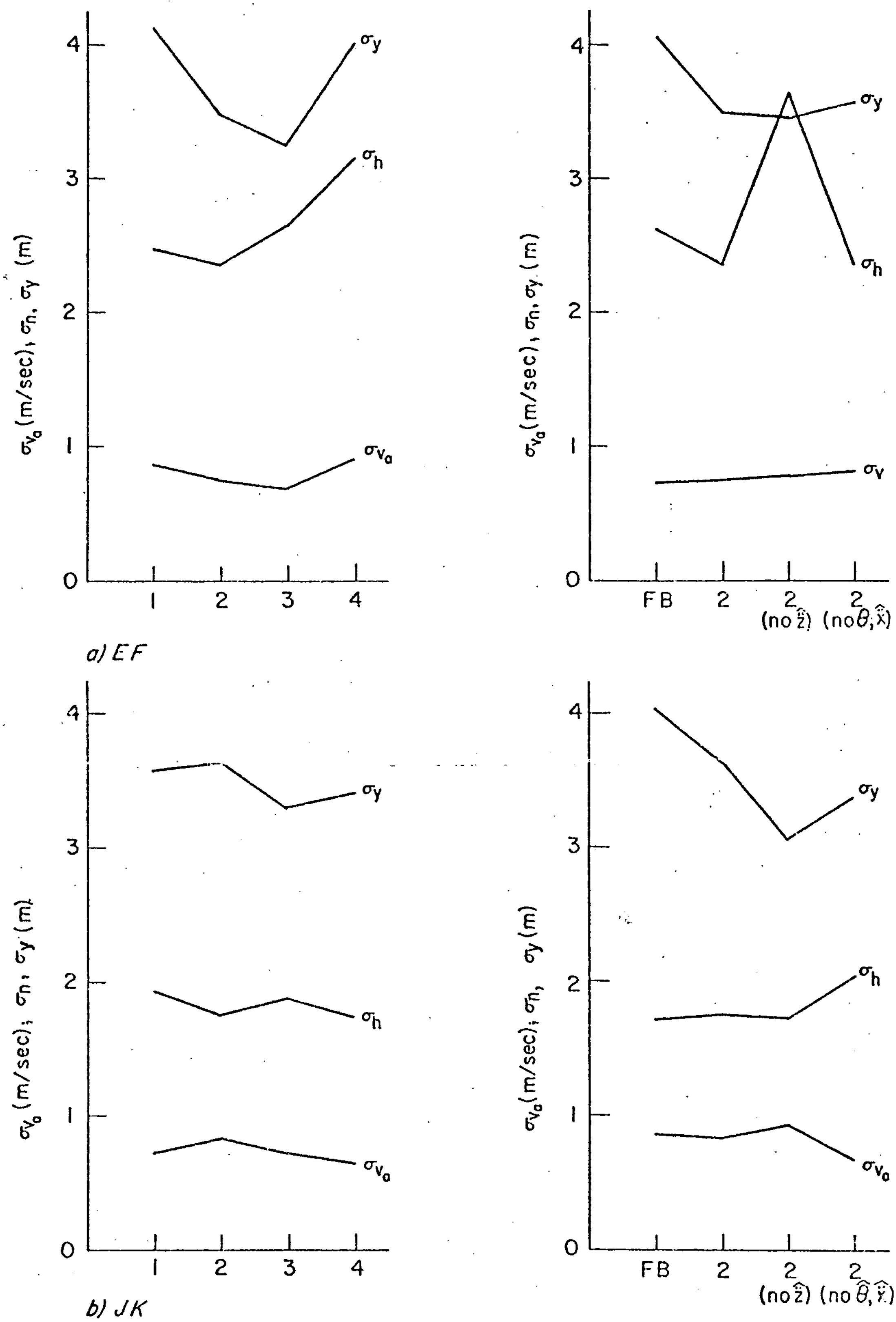

Figure 11. Averaged Performance, VFR Tracking Experiment

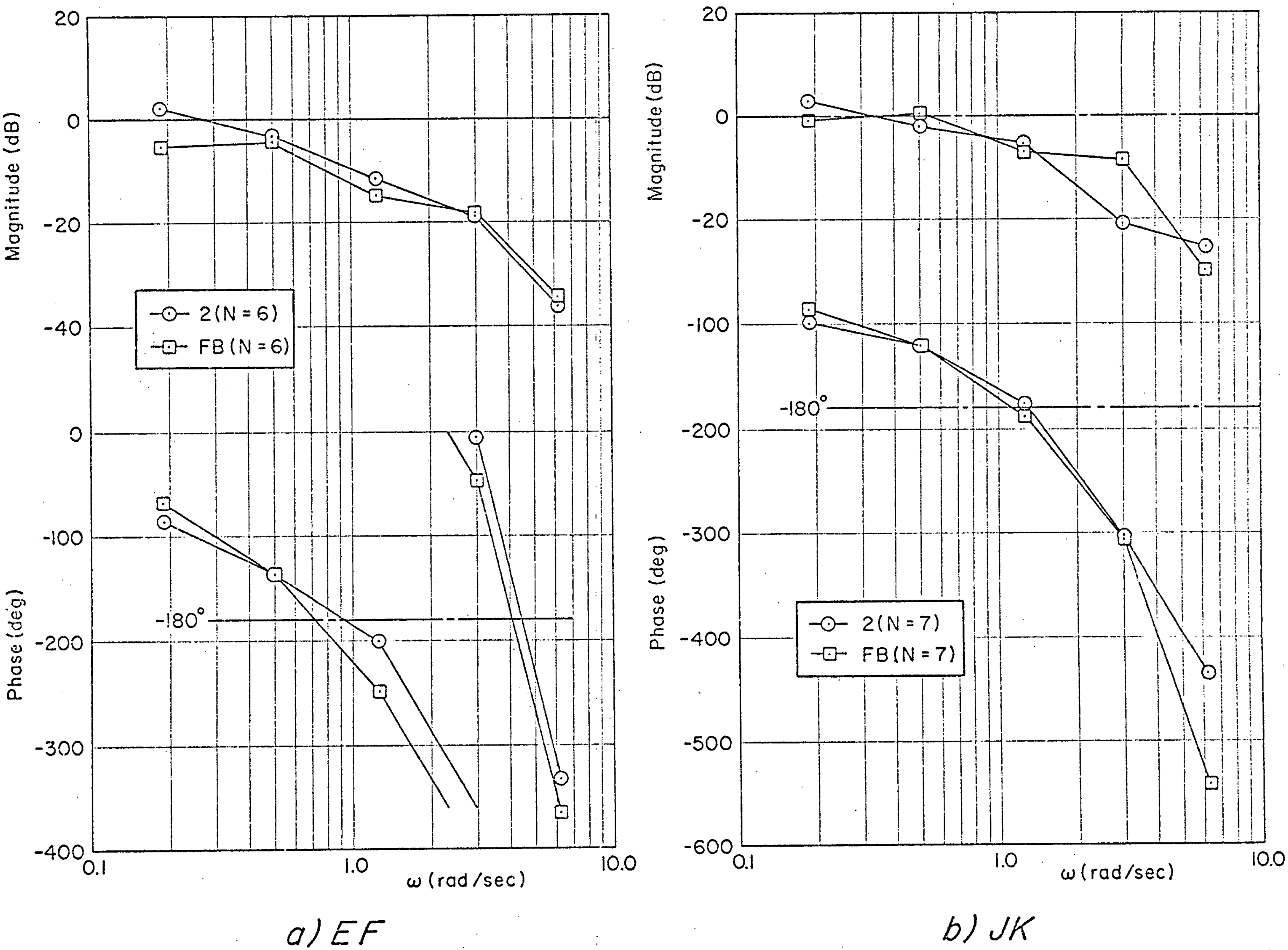

Figure 12. Describing Functions, VFR Tracking Experiment

tilt rates. These differences apparently correlate with their backgrounds of heavy helicopter and Navy jet experience, respectively.

Second, with regard to establishing the best compromise coordinated washout configuration, No. 2 (washout frequency of 0.5 rad/sec) is apparently the best for this experimental task. There is too little motion on No. 1 (0.35 rad/sec washout frequency), and too much residual tilt on Nos. 3 and 4 (washout frequencies of 0.75 and 1.0 rad/sec). Even so, there are indications in the commentary that one of the subjects, EF, finds the amount of residual tilt with Configuration No. 2 disturbing.

Thirdly, the data show that attitude control is most heavily influenced by fixed base/moving base differences. Overall performance changes, and changes in the describing function data, are insignificant. The dominant changes are in the "bandwidth" (e.g., σ_p/σ_φ) of the attitude control tasks, especially in roll. It is possible, bearing in mind the results of Section III, that inhibition or distraction effects may detract from the benefits of the motion cues.

Appendix C points out the fourth and fifth results, viz. that there is no apparent correlation between the subject's individual angular motion thresholds and performance (the subject with the higher thresholds generally has the lower attitude rates); and that the effective angular rate thresholds are relatively low — lower than the estimates of Ref. 1. These results must be qualified in that residual tilt rates may confuse the data. However JK is most sensitive to pitch rate per his measured (on the MCRD) perceptual threshold (Appendix C) yet is most tolerant of residual tilt in pitch. The subjects both achieve improved roll rate control with the presence of motion even though the root mean square (or standard deviation) of the cab roll rates is as low as 19 mr/sec. Subject commentary is also revealing: JK said the FB configuration was, "almost like IFR," implying that motion permitted a more VFR-like technique. Rates this low can improve attitude control — by the same token, anomolous rates this high (i.e., residual tilt rates) can confuse the pilot.

Finally, pilot commentary at the outset of this experiment was that the simulated visual scene provides attitude and lineup cues — both subjects relied on instrument scanning for altitude rate, altitude, and airspeed cues. Preliminary experimentation suggested that sensitivity to lineup (more precisely, lateral deviation) errors was inversely proportional to altitude as one might expect. That the visual scene replaces the attitude ball as an attitude reference is confirmed by pilot commentary to the effect that they, "wouldn't miss the attitude ball." To do this, the visual scene must move in a realistic fashion; jerkiness is not permissible.

The major conclusions to be obtained from this experiment are twofold:

- Motion cues primarily affected attitude control and had relatively little influence on path performance.

- With coordinated washout circuits there was a scale factor/break frequency trade-off. Residual tilt effects were excessive when the break frequency was too high.

The first is the same conclusion reached in the IFR tracking experiment (Section III) and is similarly subject to the same reservations — inhibiting or distracting effects arising out of the simulator's lateral motion may obscure motion benefits on performance which may otherwise be evident.

The second conclusion is subject to pilot preferences and pertains only to the tracking task context. To judge by the limited sample in this experiment (two pilots) there is a wide variation in the "optimum" compromise, depending (apparently) upon subject background. Subject sensitivity to relatively low rates, as evidenced by the motion differences exhibited, suggests that the tradeoff be in the direction of the lower residual tilt rates.

SECTION V

SUMMARY AND CONCLUDING REMARKS

The major results of this study lie in the general area of motion cue effects on STOL (specifically the AWJSRA) approach simulations. The specific results relate to the utilization of linear acceleration cues, motion threshold effects, and motion washout design. Inhibiting and distracting effects of simulator motion constitute the major unknown factor in the results. Intersubject differences were also important. Finally, there are certain implications on STOL simulation design to be drawn from the results of this study.

A. IMPORTANCE OF MOTION EFFECTS IN STOL APPROACH SIMULATIONS

The primary effect of motion cues in STOL approach is to alter the attitude control performance. The most significant (i.e., largest) changes when going from fixed-base to moving-base conditions lie in the pilot's control activity, and the vehicle's angular rates and attitudes. For the AWJSRA with stable attitude control dynamics, the effect is to decrease the effective bandwidth, as indicated by the ratio of the standard deviations of body axis rates to attitudes. This is true for both the IFR and VFR experiments in the pitch axis, and for the VFR experiment in roll. The IFR experiment was run with no lateral or directional SAS, that is, with unstable roll dynamics (a spiral divergence). In this instance, the roll bandwidth, σ_p/σ_φ, increased with the addition of motion cues.

Flight path performance, by contrast, was relatively little (and inconsistently) affected by the presence or absence of motion cues in both IFR and VFR situations. Lateral deviation control improved by approximately ten percent, moving base, in both experiments (with differing roll dynamics) but altitude or glide slope control deteriorates (IFR, by about 10%), remains about the same (VFR, for subject JK), or improves (VFR, by about 10% for Subject EF). The changes are not significant because they are small and based upon limited data (5 to 8 runs per configuration tested).

These results (significant effects on attitude control, relatively minor effects on path control) are generally in accord with past motion

C.2

simulator experience in tasks of this nature. For example, the Ref. 4 results for a hovering VTOL with stable attitude dynamics (a considerably more difficult task) were similarly inconsistent with regard to path (i.e., hovering position) control. Pre-experimental predictions for the current experiment were correct insofar as minor (if any) improvements in glide slope control with the addition of motion cues were expected.

In a qualitative sense, the addition of motion enhances the subject pilot's impression of simulation "realism." In fact, indications are that for some pilots (e.g., JK in the VFR tracking task) the motion need not be realistic (in this instance, false pitch rate cues) to convey a favorable impression. However this impression of realism can be severely compromised by simulator artifacts such as noise, rumble, vibration, and (extremely upsetting to the pilot) motion limiting.

B. UTILIZATION OF LINEAR MOTION CUES

The results of the single-axis tracking task experiment (Section II) clearly demonstrate that linear motion cues can be used to improve tracking task performance. In this experiment, the accelerations felt were proportional to the second time derivative of the displayed error and provided a useful feedback.

In the VFR experiment, one subject (JK) commented favorably on the correlation between diverter inputs and the longitudinal acceleration experiences. Similar comments to the effect that the sensed acceleration helps the pilot to gauge his control corrections (the diverter is a pure friction control) were obtained in the Ad Hoc experiment of Appendix D. The commentary suggests that linear acceleration cues can be effectively utilized when closely related to control activity.

There is some evidence in the data that less closely correlated (with control activity) linear acceleration cues can be used. When vertical accelerations were deleted, EF's performance in the VFR tracking task suffered, and his commentary noted the increased difficulty. This suggests, that for some pilots, vertical acceleration cues are important to STOL tracking performance. To others (e.g., JK) they are of little discernable benefit. In short, utilization of linear acceleration cues in STOL simulations is subject dependent.

C. MOTION THRESHOLD EFFECTS

The results demonstrate, by the changes in attitude control produced, that some pilots can utilize attitude rates having an rms level somewhat lower than 20 mr/sec in a multi-axis tracking task. This figure is somewhat lower than what might be expected based upon perceptual measurements using the Man Carrying Rotation Device and nominal values for time constants associated with the washout of sensations of angular acceleration (see Appendix C). The attitude performance achieved in this experiment does not appear correlated with the individual subject's perceptual thresholds. In fact, the apparent correlation is negative, suggesting that stylistic differences were more important in this experiment than physiological differences.

Linear accelerations having rms levels on the order of 0.05 g can be used by subjects to improve performance, regardless of direction. This suggests effective proprioceptive thresholds which are, at least to a first approximation, unaffected by the operating point (zero if longitudinal or lateral, one g if vertical). This figure (0.05 g) is not incompatible with typical values given (approximately 0.01 g) for perceptual thresholds (Ref. 8).

These results carry an obvious implication with regard to motion fidelity in a moving base simulator. Anomolous rates, such as produced by a coordinated washout scheme as used in these experiments, must be low relative to the angular rates being simulated and should be less than the pilot's effective threshold. If the current results are accepted as indicative, anomalous rates greater than 20 mr/sec are too high, at least in the context of STOL approach in light to moderate turbulence. In the Ad Hoc experiment discussed in Appendix D, the residual tilt rates were confusing to the pilots because they were correlated with the maneuvers of the task and of a comparable magnitude to the rates being simulated — there were no "masking" disturbances. In the VFR tracking experiment, there were indications that the anomalous rates were disturbing, even in the "optimum" washout, to one of the subjects. Clearly, residual tilt rates must be very small.

D. INHIBITING AND DISTRACTING EFFECTS OF MOTION

There is evidence in the describing function measurements taken in the IFR tracking experiment and in the pilot commentary elsewhere, that there are some aspects of the moving base simulator environment which are disturbing to the pilot. These can be large enough to compromise his moving base performance, thereby (perhaps) leading to erroneous results. The pilots speak of rumble, vibration, and noise in general; in particular, they mention the combination of sounds which indicates large and rapid lateral motion toward the travel limits. Contact with the motion limits is a very upsetting experience; one pilot specifically indicated that it, "was bound to affect," his control. In addition, there are apparently extraneous accelerations associated with the lateral degree of simulator freedom which may be due to twisting, or torsion, of the simulator tower. Such accelerations compromise the fidelity of the lateral acceleration cues and can presumably affect the pilot's response to these cues.

While the above remarks apply to the Six-Degrees-of-Freedom Motion Simulator specifically, they should be interpreted as general remarks as well. If the pilot is distracted by artifacts in a simulator's motion or concerned by the possibility of episodes of motion limiting, his behavior can be affected to some extent. How much depends upon the subject, task, and experimental situation, and constitutes an unknown factor in the results obtained.

E. CONCLUDING REMARKS — STOL SIMULATOR DESIGN IMPLICATIONS

At the outset of this program it was decided to use a motion washout scheme incorporating residual tilt of the simulator's cab so as to retain vehicle coordination (i.e., accurate reproduction of longitudinal and lateral accelerations — residual tilt is of no help in simulating vertical accelerations) throughout the low and intermediate frequency ranges. This decision was based on the earlier results of Ref. 4 where the lack of coordination provided a beneficial cue which the pilot would not get in flight, and on the particular interest in the effects of linear motion cues in this program. To keep the linear motions within the travel limits of the simulator, all motions were attenuated and the simulated disturbances were relatively light.

If accurate (albeit attenuated) linear acceleration cues are to be provided which the pilot can use in a continuous tracking situation, the results of this experimental study imply very low linear motion washout break frequencies (because residual tilt rates must be kept very low) and therefore, large linear travel capabilities. The results of the earlier study of Ref. 4 suggested that pilots can use utricular (and other proprioceptive) cues in the frequency range near 1 rad/sec. The single axis tracking experiment in the current program provided results confirming this. Further, most outer loop, path control tasks in aircraft generally have bandwidths less than 0.5 rad/sec. Since the pilots can use relatively low level linear acceleration cues, it implies that the fidelity requirements on these cues at these frequencies must be relatively high if the cues are to be used in a closed loop sense.

Most current simulators cannot satisfy these requirements without excessive residual tilt (exception: the FSAA at ARC in the lateral degree of freedom). It is therefore not surprising that results obtained on these simulators fail to show that linear accelerations are used by the subjects. Even if the subject is predisposed to use linear acceleration cues, the fidelity of the accelerations in the frequency range where they could be important is relatively poor or, if relatively good, then confounded by large residual tilt rates. In attempting to maximize utilization of the limited linear travel in these simulators, one runs into (literally!) another confounding factor — inhibiting the pilot because of concern with motion limiting.

If, on the other hand, the purpose of the simulator is to provide only an indication of the forces acting on the simulated aircraft, then relatively rapid washouts can be used with limited travel capabilities and with little or no residual tilt. The linear acceleration sensations are good only at the high frequencies, and it is therefore unreasonable to expect linear motion cues in such simulators to have a pronounced effect on the control of simulated linear (path) motions which are at low frequencies. The accelerations can only act as a monitor of control activity and as an indicator of the simulated environment, e.g., aerodynamic disturbances and simulated aircraft failures. However, as pointed out by the Ref. 4 results, the lack of the low frequency motion may provide (unintentionally) an additional and useful cue to the pilot.

REFERENCES

1. Stapleford, Robert L., Richard A. Peters, and Fred R. Alex, Experiments and a Model for Pilot Dynamics with Visual and Motion Inputs, NASA CR-1325, May 1969.

2. Bergeron, Hugh P., The Effects of Motion Cues on Compensatory Tracking Tasks, AIAA Paper No. 70-352, presented at the AIAA Visual and Motion Simulation Technology Conf., Cape Canaveral, Fla., March 16-18, 1970.

3. Rumsey, P. C., R. E. Spitzer, and W. L. G. Glende, Results of a Piloted Simulation of the Modified Augmentor-Wing Buffalo (Vol 1), Boeing Co. Doc. No. D6-24806-1, Jan. 1971.

4. Ringland, R. F., R. L. Stapleford, and R. E. Magdaleno, Motion Effects on an IFR Hovering Task — Analytical Predictions and Experimental Results, NASA CR-1933, Nov. 1971.

5. Clark, B., and J. D. Stewart, "Thresholds for the Perception of Angular Acceleration About the Three Major Body Axes," Acta Otolaryng, Vol. 69, 1970, pp. 231-238.

6. Malcolm, R., and G. M. Jones, Some Experiments on the Perception of Vertical Motion, Enclosure in a letter written by R. Malcolm to to G. R. Holden at ARC, October 1970.

7. Walsh, E. G., "Role of the Vestibular Apparatus in the Perception of Motion on a Parallel Swing," J. Physiol., Vol. 155, 1961, pp. 506-513.

8. Young, L. R., "The Current Status of Vestibular System Models," Automatica, Vol. 5, 1969, pp. 369-383.

9. Peters, Richard A., Dynamics of the Vestibular System and Their Relation to Motion Perception, Spatial Disorientation, and Illusions, NASA CR-1309, April 1969.

10. Cleveland, W. B., Augmentor Wing Jet STOL Research Aircraft Digital Simulation, NASA-ARC Informal Documentation, 1970.

11. Fry, Emmett B., Richard K. Greif, and Ronald M. Gerdes, Use of a Six-Degrees-of-Freedom Motion Simulator for VTOL Hovering Tasks, NASA TN D-5383, Aug. 1969.

12. Schmidt, Stanley F., and Bjorn Conrad, Motion Drive Signals for Piloted Flight Simulators, Analytical Mechanics Associates, Inc., Feb. 1970.

13. Conrad, Bjorn, and Stanley F. Schmidt, A Study of Techniques for Calculating Motion Drive Signals for Flight Simulators, NASA CR-114345, July 1971.

14. Stewart, John D. Letter to R. F. Ringland concerning measured (on the MCRD) subject perceptual angular acceleration thresholds, LTI: 239-3, 13 December 1971.

APPENDIX A

SIMULATION DESCRIPTION, PHASE II EXPERIMENTS

The VFR and IFR experiments discussed in the main text were conducted using the simulation described in this appendix. The topology of the experimental setup is illustrated in Fig. A-1.

The real-time digital computer simulation of the subject aircraft (to be described below) is fully described in Ref. 10. It was modified to include generation of the motion simulator drive signals ("washouts") and measurement of pilot-vehicle system performance.* The program uses both table look up and function generators for the aerodynamic data. These data are nonlinear and include ground effects which for the simulated airplane are negative (i.e., "suckdown"). The program features both fast and slow loops for the integration of the dependent variables. The compute cycle durations were 49 and 98 milliseconds for the two computational loops. The fast loop was used for integrating all angular accelerations and simulator drive signals (both angular and translational); the slow loop was used for integrating all other translational accelerations. All computer outputs were updated every 49 milliseconds.

VEHICLE DESCRIPTION

The airplane simulated in these experiments is the Augmentor Wing Jet STOL Research Aircraft (AWJSRA) intended for evaluation of the augmentor wing concept in STOL-type passenger aircraft. It is basically a deHavilland "Buffalo" incorporating a wing of reduced span to increase the wing loading to a level typical of a commercial STOL airplane. The augmentor wing incorporates fixed leading edge slats, augmentor flaps, and blown ailerons. Propulsion is by means of two Rolls Royce Spey engines mounted in wing nacelles. The direct, or hot thrust is through swiveled Pegasus nozzles while the cold flow is ducted to the augmentor flaps and the blown ailerons.

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*Additional modifications of a more minor nature included deletion of the longitudinal control system dynamics and the thrust diverter loops. Provision was made for altitude acceleration disturbances ($\ddot{h}_d$) used in the describing function measurements.

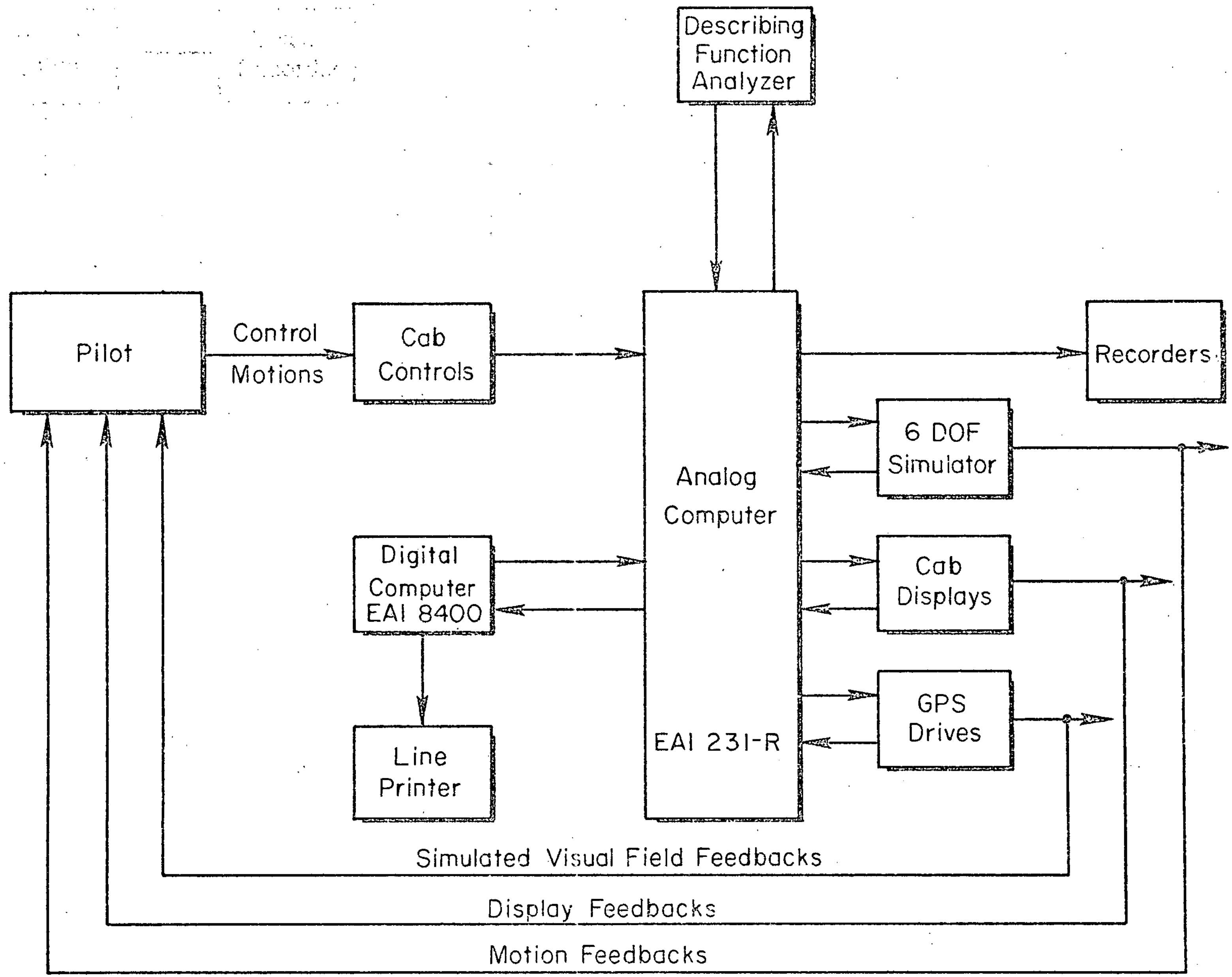


Figure A-1. Topology of Experimental Setup

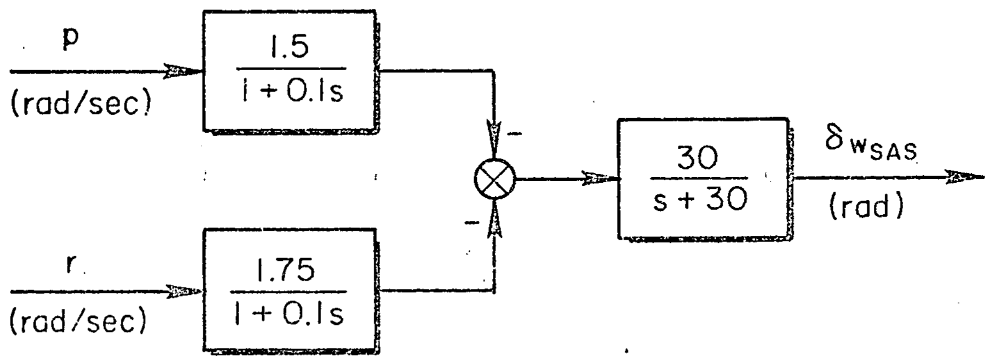
Longitudinal control is effected with elevator, throttle and thrust diverter controls; lateral control by rudder deflection and a geared combination of aileron and spoiler deflection with choking of the flow through the outboard augmentor flap. The simulated aircraft employs both a lateral and directional stability augmentation system, the linearized equivalent of which is shown in Fig. A-2. The SAS was used in only the VFR tracking experiment, being turned off for the IFR experiment.

In the IFR experiment an approach flight condition was simulated having an airspeed of 30.9 m/s (60 kts), −0.131 rad (−7.5 deg) flight path angle, with a gross weight of 18,130 kg (40,000 lb). In this condition, the flaps are deflected to 1.134 rad (65 deg), the ailerons are drooped to 0.525 rad (30 deg), and the Pegasus nozzles are directed almost vertically at approximately 50% of rated hot thrust. For the VFR experiment, the flight condition was similar except that the thrust level was increased substantially (to about 90%) to hold a level flight path at the same airspeed with the nozzles deflected slightly aft of vertical.

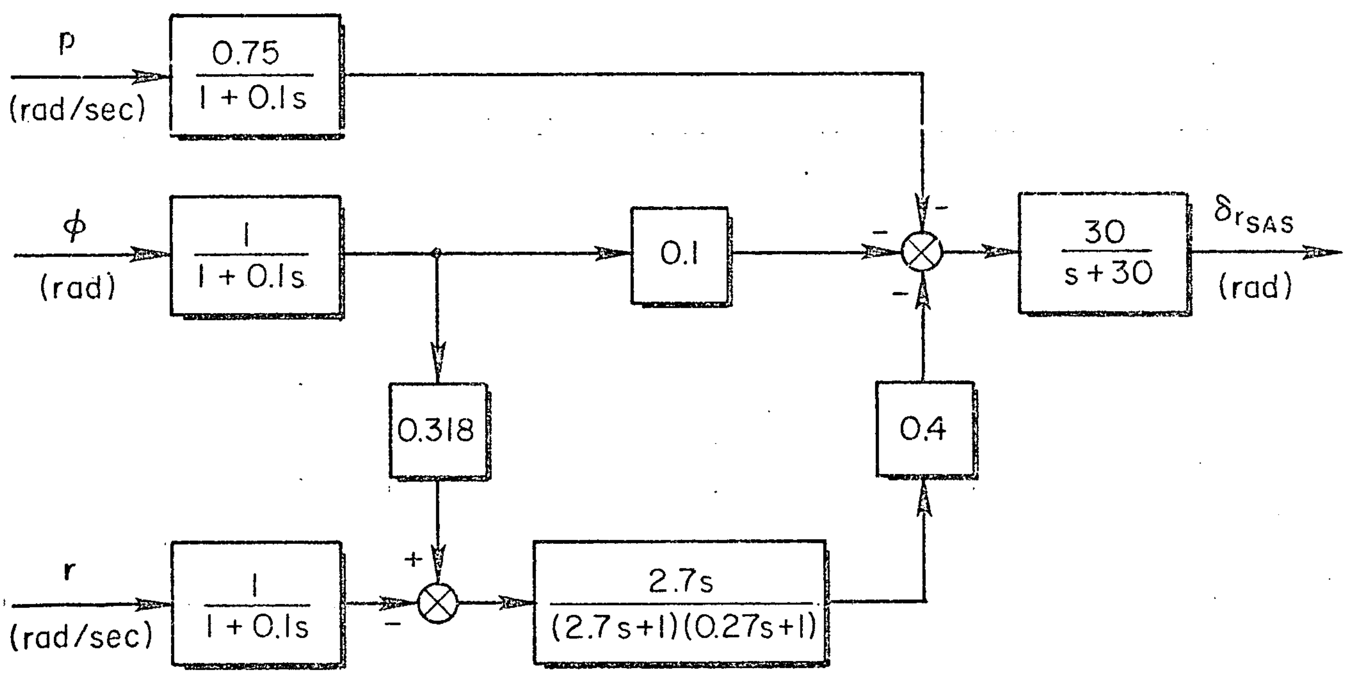
In either of these flight conditions the longitudinal handling qualities of the airplane suffer from low control sensitivity for control of flight path (see Table B-2). Without SAS, the lateral dynamics are dominated by a relatively rapid spiral divergence — with SAS the divergence is eliminated. Pre-experimental analyses of this airplane indicated a relatively low sensitivity to the presence or absence of motion cues. That is, path control performance would show only slight improvement with motion — attitude control, however, could be expected to improve, moving base. These analyses also suggested the possibility that vertical (heave) accelerations might be used by the pilot in control of flight path — here again, low control power would limit the performance improvements possible.

CONTROLLERS

Control of the simulated vehicle was effected differently from the actual airplane, using a two-axis center stick (instead of column and yoke), pedals, and console mounted throttle and thrust diverter (nozzle angle) controls to the pilot's left (instead of overhead controls to his right). There was no flap control, the flaps being fixed for the experiment. The



a) Lateral SAS



b) Directional SAS

Figure A-2. Stability Augmentation Systems controllers in all cases were scaled so that the full deflection of the cab controls corresponded to full deflection of the simulated aircraft controls. The controller characteristics are listed in Table A-1. They were all regarded as satisfactory by the pilot subjects.

DISPLAYS

The instrument panel was located approximately 66 cm from the pilot's eyes. Its layout is indicated in Fig. A-3 and illustrated in the photograph of Fig. A-4. The ADI comprized a 7.6 cm ball for display of aircraft pitch, yaw, and roll attitude; horizontal and vertical bars for display of glide slope and localizer errors, and a turn/sideslip indicator. The scaling of the bars was such that full deflection of the horizontal bar corresponded to 52.4 mr of glide slope error; full deflection of the vertical bar corresponded to 104.8 mr of localizer error. The usual scaling for an ILS indicator is 8.74 mr and 43.7 mr, respectively — the experimental setup is considerably less sensitive. The ILS needles were fed by signals corresponding to fixed ranges (1263 m, glide slope; 1755 m, localizer) from the antennas. For the VFR experiment, they were disabled.

Both sideslip indicators (the one on the ADI and the separate instrument) were scaled for 1 cm deflection corresponding to 0.1 g of lateral acceleration. The turn indicators were scaled such that full deflection (two needle widths) corresponded to a one minute turn (0.1045 rad/sec yaw rate).

Of all the instruments, only the compass and airspeed indicators had lags within the frequency range of interest; approximately 0.3 sec (compass) and 0.15 sec (IAS). All other indicators (except trim) had lags of less than 0.1 sec based on measured amplitude versus frequency characteristics. These remarks apply to the instrument, its drive servos (if a 400 Hz instrument), and any filtering used to smooth the digital computer's output. In some instances, considerable filtering was required because of the relatively slow computer update rate (every 49 ms).

For the VFR experiment, the visual scene was generated by Ames Research Center's Visual Flight Attachment IV (GPS), a visual display system employing a moving belt for the longitudinal degree of freedom. It was presented to

TABLE A-1. CONTROLLER CHARACTERISTICS

CONTROLLER	SYMBOL	BREAKOUT (N)	HYSTERESIS (N)	FULL DEFLECTION (N)	FULL DEFLECTION	FULL DEFLECTION IN AIRPLANE
Centerstick (pitch)	δ_c	8.9	6.7	49.0	8.3 cm	−15.9 cm +43.8 cm*
Centerstick (roll)	δ_w	8.9	6.7	28.9	8.3 cm	±1.361 rad
Pedals	δ_p	44.5	≐ 22.2†	200.0	5.1 cm	10.7 cm
Throttle	δ_{Th}	Friction level adjusted by pilot			≐ 1.57 rad	0.674 rad
Diverter	ν	Friction level adjusted by pilot			≐ 1.57 rad	1.702 rad‡

*Scaled for larger number, i.e., aft (positive) deflection of 8.3 cm in simulator cab represented a positive deflection of 43.8 cm in airplane.

†The force characteristics are somewhat more complex than indicated. There was an uncertainty of approximately ±0.63 cm in the pedal centering coupled with a near-zero force gradient for the next 0.6 cm of pedal travel. The poor centering characteristic was alleviated by using a small electrical dead zone.

‡From 0.323 to 2.025 rad of nozzle angle, ν.

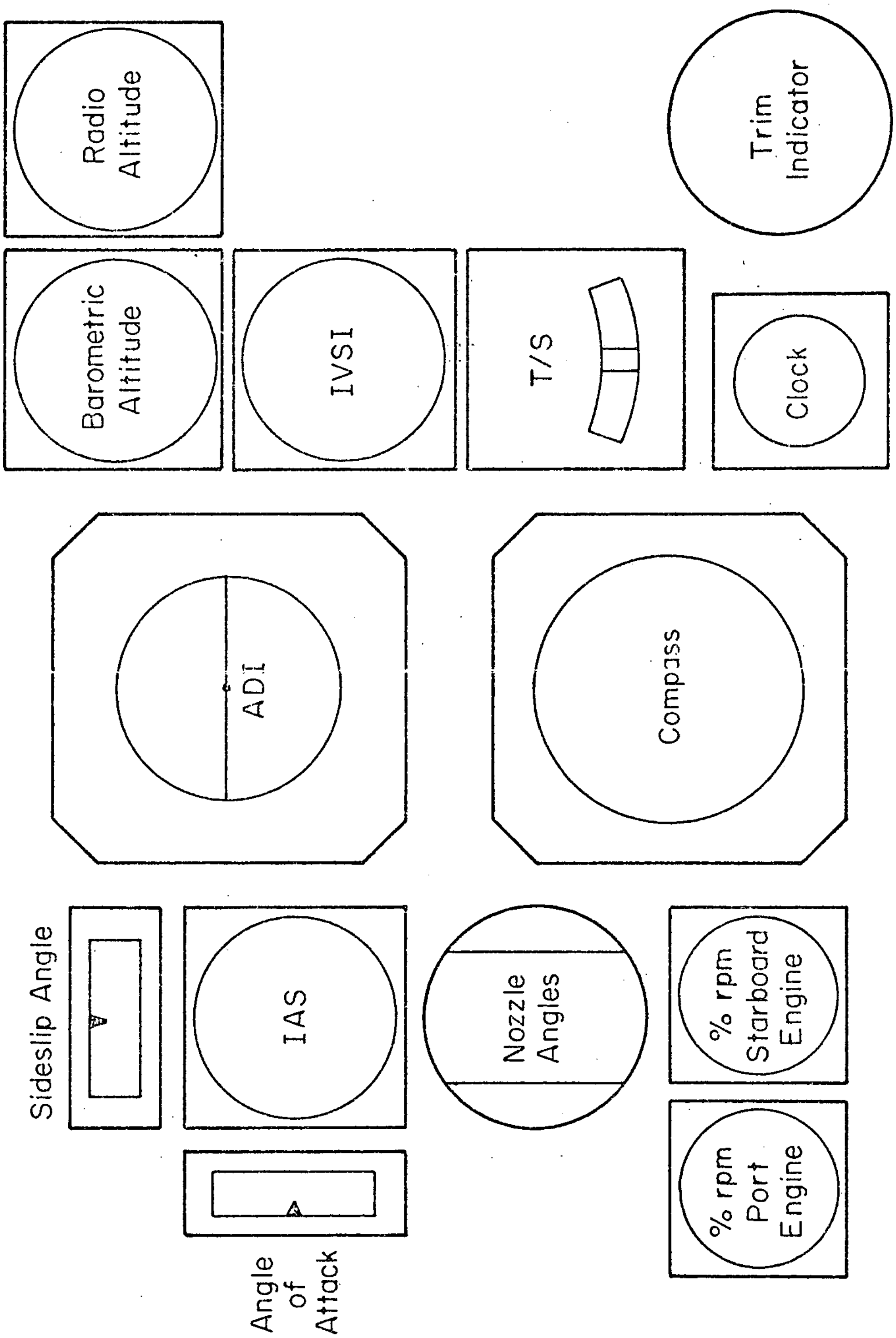


Figure A-3. Panel Layout

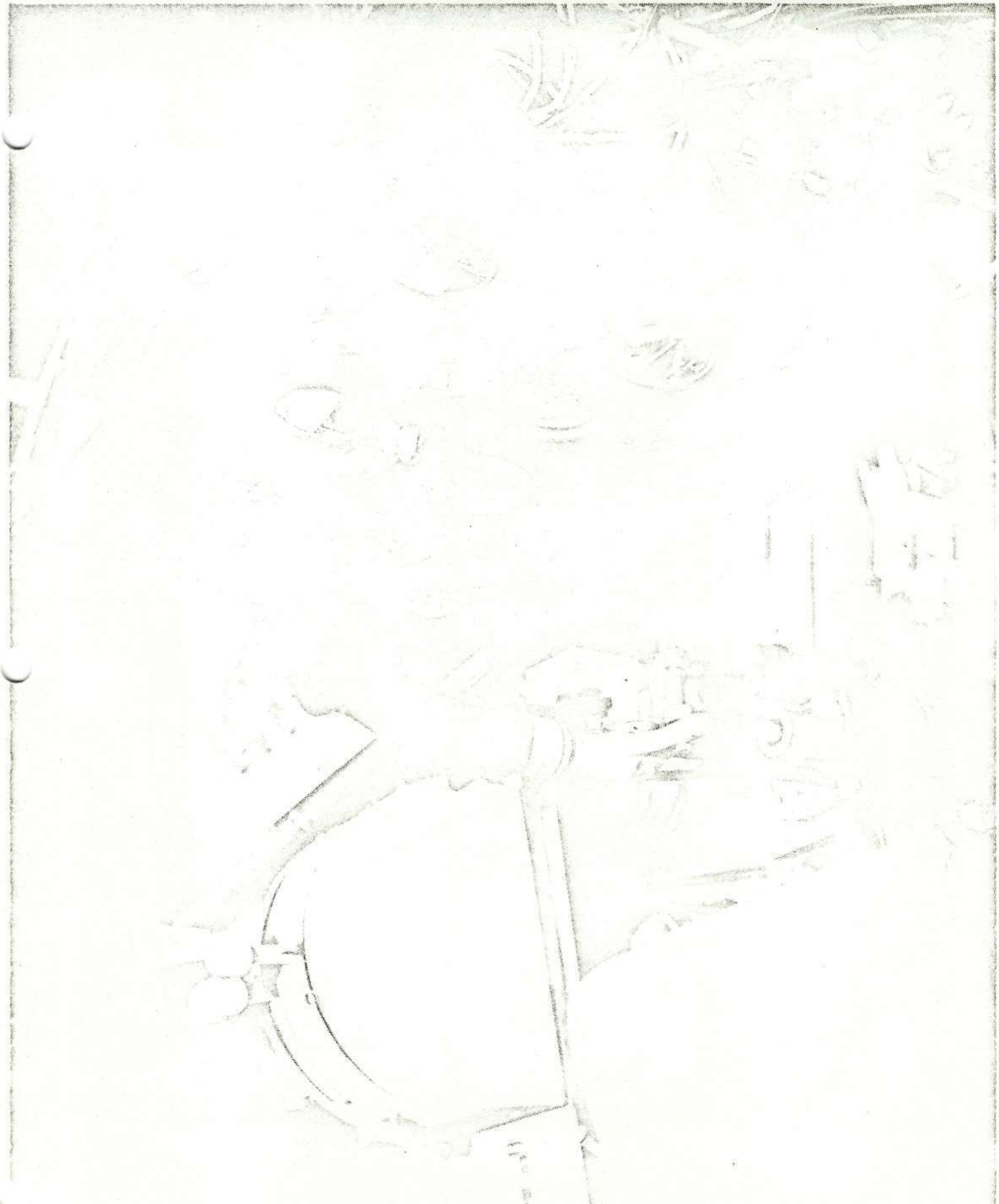


Figure A-4. Motion Simulator Cab Interior Without TV Monitor the pilot by means of a black and white TV monitor mounted on the shelf (visible in the photograph of Fig. A-4) above the instrument panel. The center of the 61 cm screen was located approximately 53 cm from the pilot's eyes.

DISTURBANCE INPUTS

The longitudinal task disturbance was provided by the describing function analyzer (DFA) in the form of an altitude acceleration disturbance, $\ddot{h}_d$. This was composed of a random-appearing sum of five sine waves whose characteristics are shown in Table A-2. To the pilot, it manifested itself as vertical gustiness of light to moderate amplitude.

TABLE A-2

DISTURBANCE SPECTRUM*

FREQUENCY (rad/sec)	ACCELERATION AMPLITUDE, $\ddot{h}_d$ (m/sec^2)	EQUIVALENT ALTITUDE DISTURBANCE, h_d (m)
0.1886	0.0677	1.905
0.503	0.203	0.804
1.257	0.203	0.129
3.016	0.203	0.022
6.283	0.203	0.005

The lateral task disturbances were simulated by feeding prerecorded white noise through "gust filters" each having a first order lag characteristic. The amplitudes and filter frequencies are indicated in Table A-3. For repeatable time averaged performance measures, each input consisted of a 100 sec long noise sample repeated over and over — a different sample for each of the two inputs. The mean value of these inputs was nominally zero. However slowly varying biases in either the reproducer or in the original recording of the 100 sec tape loop introduced the equivalent of a mean wind (averaged over 100 sec) which varied between 0 and 0.5 m/sec blowing from the right and causing the aircraft to drift left.

*$\sigma_{\ddot{h}_d} = 0.412\ m/sec^2$, $\sigma_{h_d} = 2.06$ m.

TABLE A-3

SIMULATED LATERAL GUST CHARACTERISTICS

SYMBOL	AMPLITUDE	INVERSE FILTER TIME CONSTANT
v_{BN}	$\sigma_{v_{BN}} = 0.96$ m/sec	$1/\tau_{v_{BN}} = 0.105\ \text{sec}^{-1}$
p_{BN}	$\sigma_{p_{BN}} = 0.0136$ rad/sec	$1/\tau_{p_{BN}} = 1.000\ \text{sec}^{-1}$

MOTION SIMULATOR AND COMPENSATION

The motion simulator used in these experiments was the Six-Degrees-of-Freedom Motion Simulator (S.01) at Ames Research Center (Fig. A-5), designed for V/STOL research. The cab rotates about all three axes [rotation order is roll (inner gimbal), yaw (middle gimbal) and pitch (outer gimbal)] and translates up and down (±2.5 m travel) on the front of the tower. The tower moves longitudinally and laterally (±2.7 m travel in each direction) for the $\hat{x}$ and $\hat{y}$ degrees of freedom.

Measurement of the simulator failed to reveal any significant differences in the simulator response from earlier measurements, e.g., Ref. 11. Consequently, the simulator was compensated against these characteristics as in other programs using an equation of the form:

$$\lambda_c = \lambda_s + K_1\dot{\lambda}_s + K_2\ddot{\lambda}_s \qquad \text{(A-1)}$$

where λ_c is the simulator command and λ_s the computer value. Table A-4 lists the values of the compensatory coefficients, K_1 and K_2:

TABLE A-4. MOTION SIMULATOR COMPENSATION

AXIS	K_1 (sec)	K_2 (sec^2)
Roll, $\hat{\varphi}$	0.08	0
Pitch, $\hat{\theta}$	0.18	0.012
Yaw, $\hat{\psi}$	0.08	0
Longitudinal, $\hat{x}$	0.22	0.033
Lateral, $\hat{y}$	0.21	0.028
Vertical, $\hat{z}$	0.17	0.020

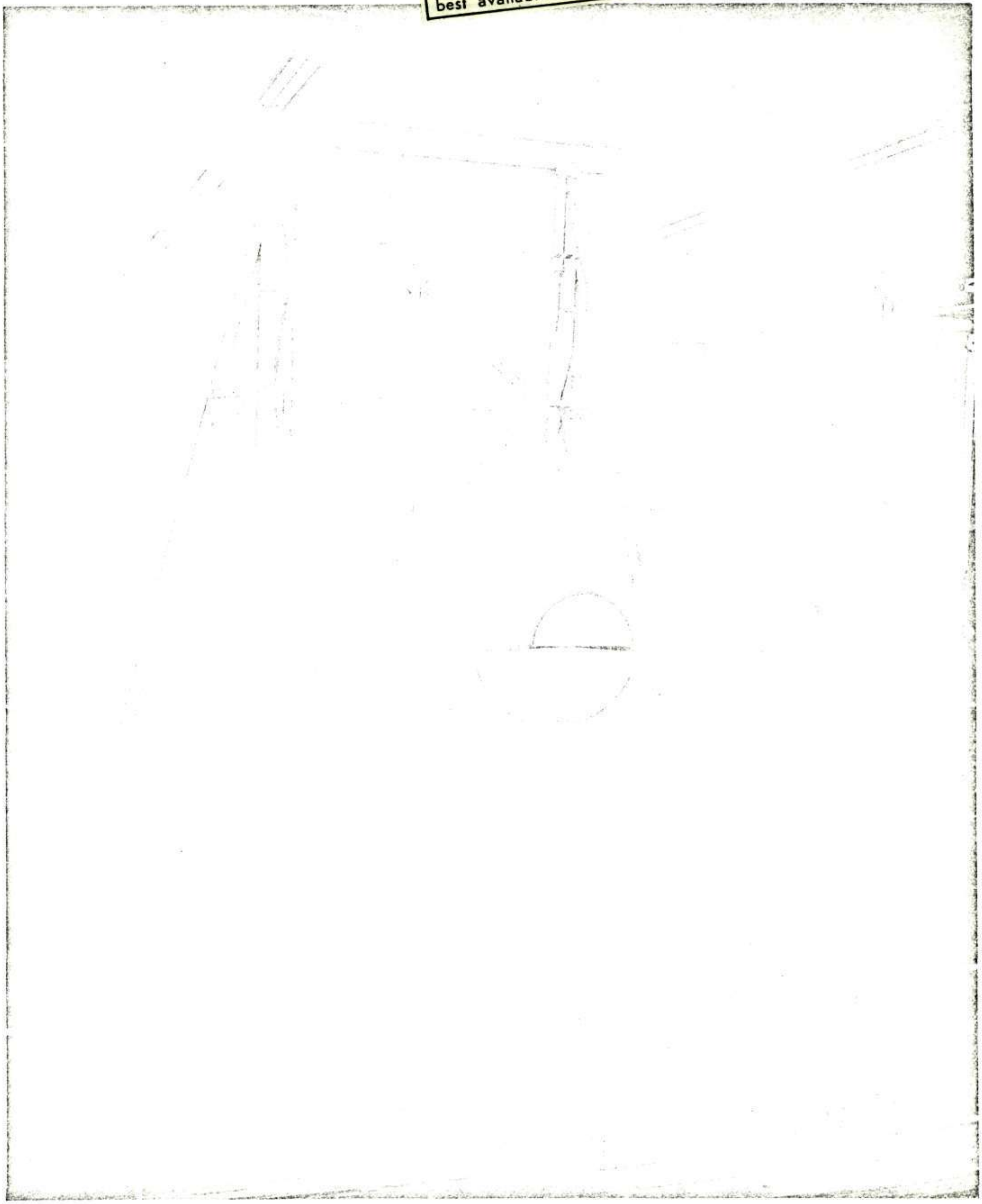


Figure A-5. Six Degrees of Freedom Motion Simulator

WASHOUT CONFIGURATIONS

One of the major criteria governing the configurations of the experiments was that the linear motion cues be simulated with good fidelity over a wide frequency range, in particular, at the relatively low frequencies where they could be of use in flight path control. The relevance of such cues in STOL simulations was a primary area of interest. To this end, a coordinated washout scheme was used. The size of the simulated disturbances and the parameters of the washout were so selected as to take maximal advantage of the linear travel capabilities of the Six-Degrees-of-Freedom Motion Simulator. During practice or training runs this resulted in occasional (sometimes frequent, if the subject was having a bad day) episodes of running into the simulator travel limits.

The coordinated washout scheme used in these experiments was developed in Refs. 12 and 13 and is illustrated (excluding the simulator compensation and motion limiting scheme) in Fig. A-6. In this figure the blocks labeled $T_{i/c}(\hat{\varphi},\hat{\theta},\hat{\psi})$ or $T_{c/i}(\hat{\varphi},\hat{\theta},\hat{\psi})$ represent transformations from cab coordinates to inertial coordinates or vice versa — they are transformation matrices. Similarly, $M(\hat{\varphi},\hat{\theta},\hat{\psi})$ represents a transformation from body axis rates to Euler (cab) angle rates.

In this scheme, small cab tilt angles are used to provide the sensation of low frequency translational accelerations in cab coordinates. For small angles, the simulator cab rates are given by*:

$$\begin{bmatrix} \dot{\hat{\varphi}} \\ \dot{\hat{\theta}} \\ \dot{\hat{\psi}} \end{bmatrix} \doteq \frac{K_\omega(0)^3}{(1/T)[\zeta,\omega]} \begin{bmatrix} p \\ q \\ r \end{bmatrix} + \frac{K_{1s}K_{2s}K_f\omega_s^2(0)(a)(b)}{(1/T)[\zeta,\omega][\zeta_s,\omega_s]} \begin{bmatrix} -a_{y_p} \\ a_{x_p} \\ 0 \end{bmatrix} \qquad \text{(A-2)}$$

where the second term represents the false rate cue due to residual tilt. The derived quantities T, ζ, ω, a, and b in this and subsequent equations result from the closed loop implicit in Fig. A-6. The residual tilt rates

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*Throughout this report, a shortened notation is used, viz:

$(1/T)$ implies $(s + 1/T)$

$[\zeta,\omega]$ implies $[s^2 + 2\zeta\omega s + \omega^2]$

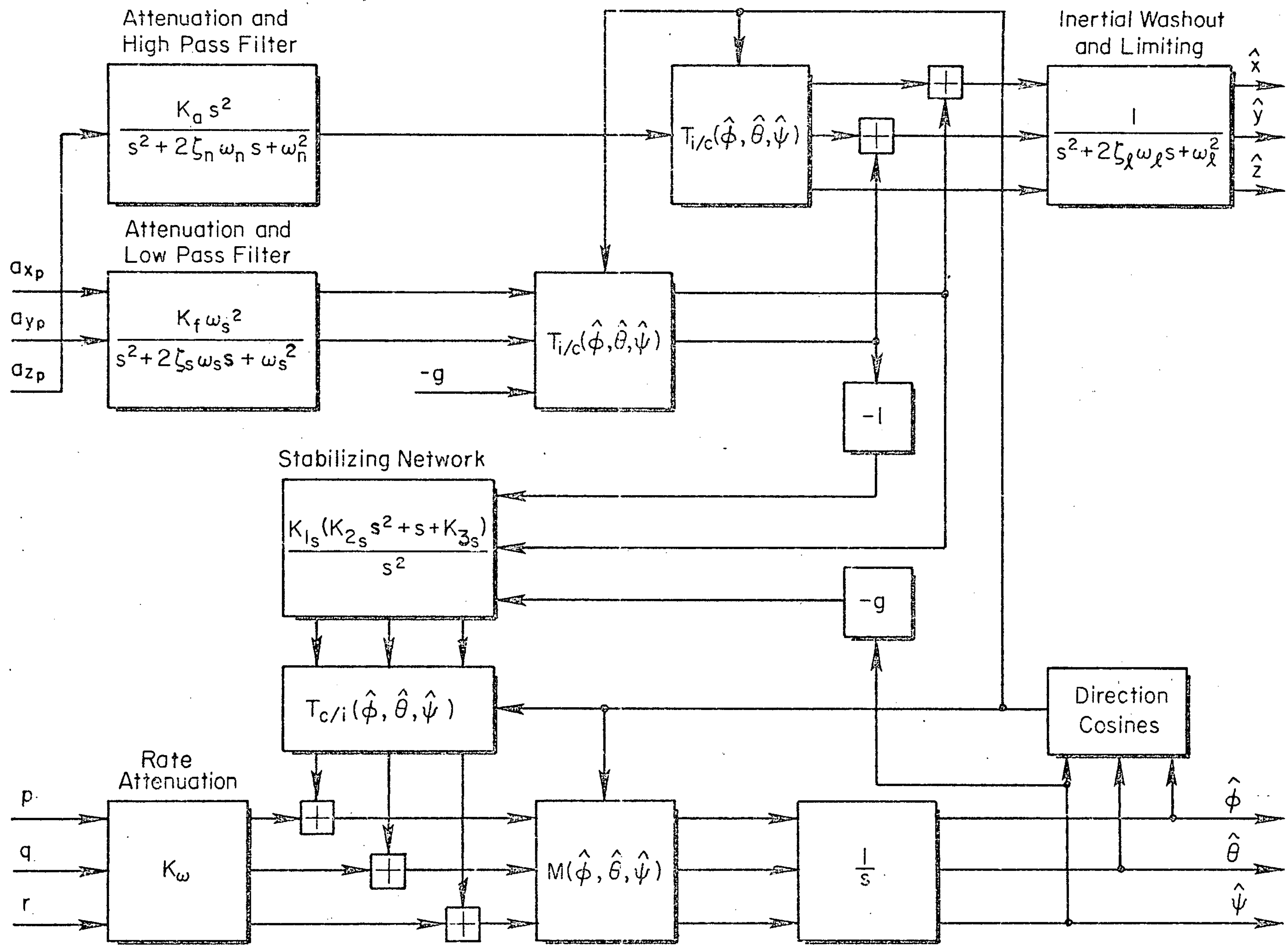


Figure A-6. Coordinated Washout Scheme

generated by the stabilizing network modify the transformation matrices which in turn alter the inputs to the stabilizing network.

The cab translational accelerations are given by:

$$\begin{bmatrix} \hat{\ddot{x}} \\ \hat{\ddot{y}} \\ \hat{\ddot{z}} \end{bmatrix} \doteq \frac{(0)^2}{[\zeta_\ell,\omega_\ell]} \left\{ \frac{K_f\omega_s^2(0)^3}{(1/T)[\zeta,\omega][\zeta_s,\omega_s]} \begin{bmatrix} a_{x_p} \\ a_{y_p} \\ 0 \end{bmatrix} + \frac{K_a(0)^2}{[\zeta_n,\omega_n]} \begin{bmatrix} 0 \\ 0 \\ a_{z_p} \end{bmatrix} + \frac{K_\omega g(0)^2}{(1/T)[\zeta,\omega]} \begin{bmatrix} -q \\ p \\ 0 \end{bmatrix} \right\} \tag{A-3}$$

Five separate washout configurations were used in the course of the IFR and VFR tracking experiments. The values of the various parameters are listed in Table A-5. Configuration 0 was used in the IFR experiment while the remaining configurations were used in the VFR experiment.

The linear motion washout responses of this coordinated scheme are shown in the sketches of Fig. A-7. They are fourth and fifth order washouts — even a bias in the computed acceleration will not result in a simulator cab steady-state position different from zero.

The accelerations (specific forces) sensed by the pilot are given by:

$$\begin{bmatrix} \hat{a}_{x_p} \\ \hat{a}_{y_p} \\ \hat{a}_{z_p} \end{bmatrix} = \begin{bmatrix} \hat{\ddot{x}} \\ \hat{\ddot{y}} \\ \hat{\ddot{z}} \end{bmatrix} + g \begin{bmatrix} \hat{\theta} \\ -\hat{\varphi} \\ -1 \end{bmatrix} \tag{A-4}$$

Performing the indicated substitutions from Eqs. A-2 and A-3 yields:

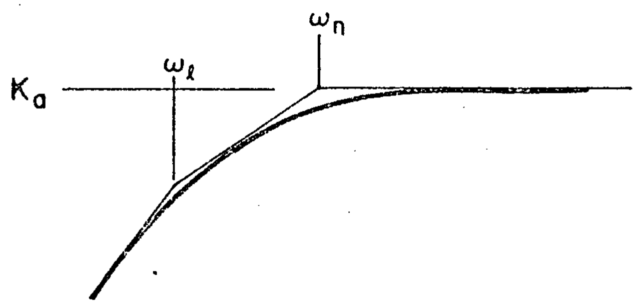
$$\begin{bmatrix} \hat{a}_{x_p} \\ \hat{a}_{y_p} \\ \hat{a}_{z_p} \end{bmatrix} = \frac{K_f\omega_s^2}{[\zeta_s,\omega_s]} \left\{ \frac{(0)^5 + K_{1a}K_{2s}g(a)(b)[\zeta_\ell,\omega_\ell]}{(1/T)[\zeta_\ell,\omega_\ell][\zeta,\omega]} \right\} \begin{bmatrix} a_{x_p} \\ a_{y_p} \\ 0 \end{bmatrix} + \frac{2\zeta_\ell\omega_\ell K_\omega g(0)^2(\omega_\ell/2\zeta_\ell)}{(1/T)[\zeta_\ell,\omega_\ell][\zeta,\omega]} \begin{bmatrix} q \\ -p \\ 0 \end{bmatrix} + \frac{K_a(0)^4}{[\zeta_\ell,\omega_\ell][\zeta_n,\omega_n]} \begin{bmatrix} 0 \\ 0 \\ a_{z_p} \end{bmatrix} \tag{A-5}$$

TABLE A-5. COORDINATED WASHOUT CONFIGURATIONS*

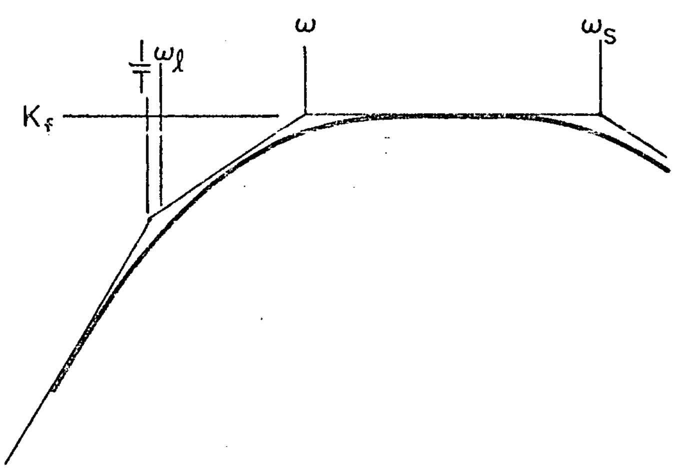
	ATTENUATION AND HIGH PASS FILTER			ATTENUATION AND LOW PASS FILTER			RATE ATTEN.
CONFIG.	K_a	ζ_n	ω_n (sec^{-1})	K_f	ζ_s	ω_s (sec^{-1})	K_ω
0	0.5	0.7	0.5	0.5	0.7	5.0	0.5
1	0.75	0.7	0.35	0.75 (a_{x_p}) 0.35 (a_{y_p})	0.7	10.0	0.75 (q) 0.35 (p,r)
2	1.0	0.7	0.5	1.0 (a_{x_p}) 0.5 (a_{y_p})	0.7	10.0	1.0 (q) 0.5 (p,r)
3	1.0	0.7	0.75	1.0 (a_{x_p}) 0.75 (a_{y_p})	0.7	10.0	1.0 (q) 0.75 (p, r)
4	1.0	0.7	1.0	1.0	0.7	10.0	1.0

	STABILIZING NETWORK			DERIVED QUANTITIES				
CONFIG.	K_{1s} (m^{-1})	K_{2s} (sec)	K_{3s} (sec^{-1})	1/T (sec^{-1})	ζ	ω (sec^{-1})	a (sec^{-1})	b (sec^{-1})
0	0.0328	2.50	0.075	0.095	0.715	0.511	0.100	0.300
1	0.0150	3.70	0.0416	0.05	0.707	0.35	0.0515	0.219
2	0.02905	2.69	0.0438	0.05	0.707	0.50	0.0506	0.326
3	0.0628	1.805	0.0457	0.05	0.707	0.75	0.0505	0.504
4	0.1091	1.35	0.04165	0.05	0.707	1.00	0.0503	0.686

*The inertial washout was the same for all configurations, viz: $\zeta_\ell = 0.7$, $\omega_\ell = 0.1\ sec^{-1}$. The limiting scheme is described in Ref. 13. It effectively prevents the motion from exceeding ±2.44 m (soft limit).



a) Vertical Acceleration Washout, $\frac{\hat{\dot{z}}}{a_{z_p}}$



b) Longitudinal and Lateral Acceleration Washouts, $\frac{\hat{\ddot{x}}}{a_{x_p}}$ and $\frac{\hat{\ddot{y}}}{a_{y_p}}$

Figure A-7. Sketches of Linear Motion Washout Frequency Responses

In this expression, the second term represents a residual force response to the simulated aircraft rates.

The responses of importance to simulator fidelity are the cab rates and specific forces. These are sketched (for the longitudinal task — similar sketches apply to the lateral variables) in Fig. A-8. The force response (a) is very nearly flat out to the low pass filter break point at ω_s — it would be exactly flat out to ω_s if no inertial washout (the box in the upper right hand corner of Fig. A-6) were used. Unfortunately, the low frequency inertial washout is necessary to eliminate very low frequency drifts in the commanded cab position which apparently result from the nature of the numerical integration.

The cab rates are washed out (b) — a third order washout. This happens because the action of the washout is to maintain the specific force at its correct value. Given an input rate, q, the cab will initially translate to hold $\hat{a}_{x_p}$ fixed, then return toward zero under the action of the linear motion washout. To keep a fixed $\hat{a}_{x_p}$, the cab tilts, thus washing out the pitch rate.

The lower two sketches in Fig. A-8 illustrate other losses in fidelity. The residual tilt response is sketched in (c). To maintain low frequency specific forces while washing out the linear acceleration requires that the cab tilt, producing a tilt rate. Sketch (d) shows similar errors in the specific force due to simulated aircraft rates. This last error would not exist if inertial motion washouts were not used.

For a given allowable linear travel Fig. A-7 shows that one can trade ω (or ω_n) against K_f (or K_a) — the scale factor can be increased as ω increases. Since $K_{1_s}K_{2_s}$ is proportional to ω, sketch (c) of Fig. A-8 shows that the residual tilt rates increase with both ω and K_f. For a given simulator travel, the residual tilt rates increase as the washout break frequency, ω, increases — this is the basic tradeoff in the coordinated washout scheme.

DATA TAKING PROCEDURES

The largest body of data taken in these experiments consists of time averaged measures of the mean and variance of several motion variables.

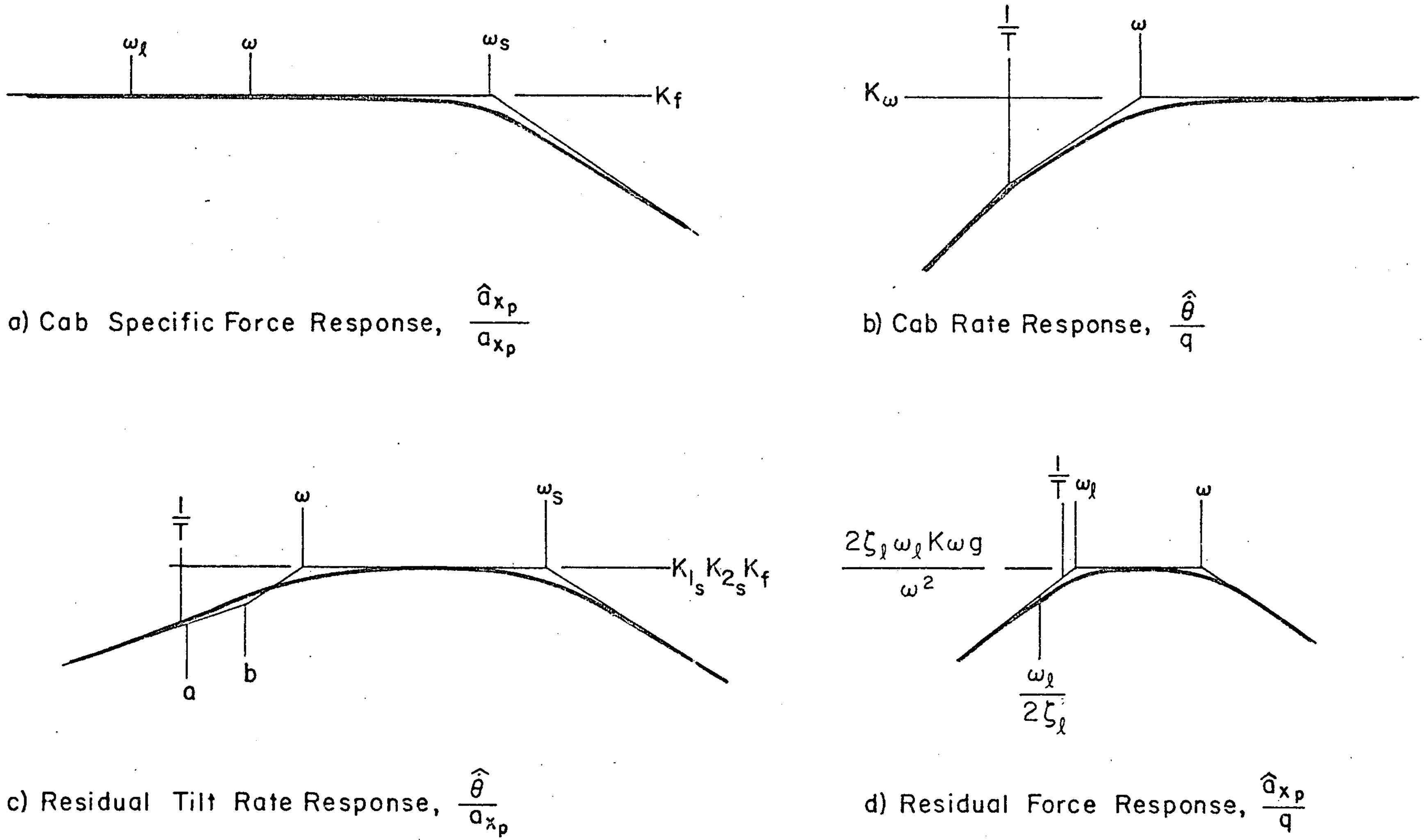


Figure A-8. Sketches of Coordinated Washout Frequency Responses

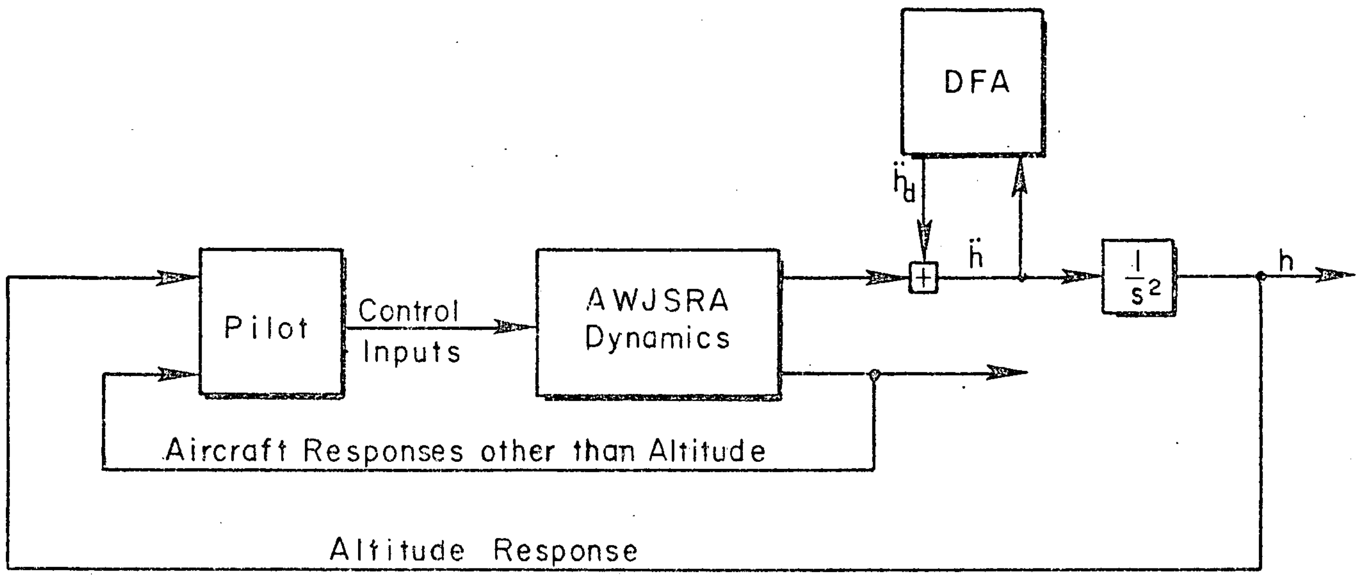
These were computed by means of a subroutine of the main simulation program, and were printed out at the end of each run.

The method used in making the describing function measurements is schematically indicated in Fig. A-9. The describing function analyzer provides a vertical acceleration disturbance, $\ddot{h}_d$, and correlates the resultant vertical acceleration, $\ddot{h}$, with this to obtain the describing function. The measured error-to-input describing function takes the form:

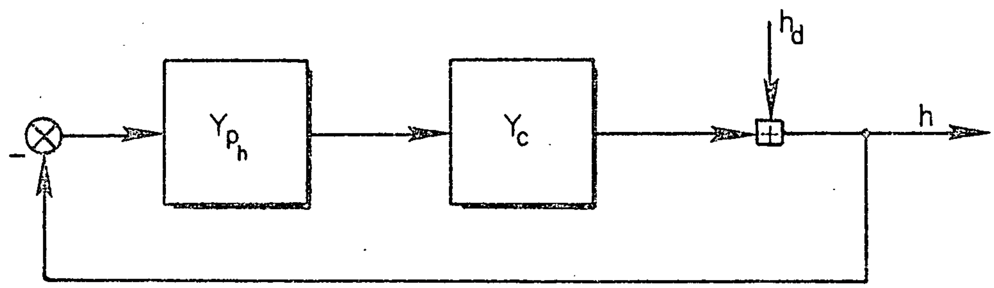
$$\frac{h}{h_d} = \frac{1}{1 + Y_{p_h} Y_c} \tag{A-6}$$

where $Y_{p_h} Y_c$ is the effective pilot-vehicle open-loop describing function in the altitude control task. Y_c is the effective altitude response transfer function with the inner loops (attitude and airspeed) closed. The measurement was made in terms of accelerations for programming convenience — the subroutine which computes the simulator motions operates on commanded accelerations, not velocities or positions. The measurement therefore was less accurate than desirable at the lowest frequencies near crossover (0.10 to 0.5 rad/sec). This was demonstrated by poor measurement repeatability at the lowest two frequencies when calibration runs were made with no V_N or P_N disturbances and either with or without an analog pilot — situations where the repeatability can be expected to be relatively high. These variations can be attributed to several factors. First, there is the small low frequency transient produced by slight mistrimming of the aircraft. When coupled with variations in the describing function measurement start time (5 to 10 seconds after the problem is started) this produces variable amounts of low frequency power. Secondly, the computing equipment may be subject to drifts in the difference between the ground potential at the analog computer console and the analog-to-digital and digital-to-analog interfacing rack located several feet away. Reference drifts within this interfacing rack are a third possible source of low frequency noise power.

The measurements of $Y_{p_h} Y_c$ at the high frequencies far from crossover were also somewhat noisy, but for a different reason: obtaining $Y_{p_h} Y_c$ from the measured $\ddot{h}/\ddot{h}_d$ (in itself, repeatable within a small percentage)



a) Mechanization



b) Equivalent Block Diagram

Figure A-9. Describing Function Measures amounts to obtaining small differences between large numbers. Fortunately, measurement accuracy is not critical in this region.

The measurements themselves (actually the real and imaginary parts of the error-to-disturbance describing function at each measurement frequency) were recorded by hand from voltage readings on the describing function analyzer at the end of each run. These were corrected for known biases in the readings before processing off-line for the open-loop describing function, $Y_{p_h}Y_c$.

Pilot comments were noted by the experimenter when significant remarks were made. Performance during the run was monitored using the strip chart recorders. These recorders were also used on occasion to monitor the motion simulator and visual display system position feedbacks, and feedbacks from the 400 Hz cab instrument drive servos.

APPENDIX B

PHASE I EXPERIMENT

The experimental data from the Phase I experiment were obtained in 31 runs over a three-day period with a NASA research pilot as the subject. These data were exploratory in nature and comprised a comparison of fixed base (FB) and moving base (MB) conditions with and without lateral and directional stability augmentation systems (SAS) under IFR conditions. The primary measurements were time averaged error variances over a 100-sec time interval. Pilot commentary was also noted.

EXPERIMENTAL PROTOCOL

The training period consisted of one day of practice (about 20 runs) primarily in the fixed base condition with SAS, with and without disturbance inputs. The subject was familiar with an earlier simulation of the AWJSRA using the Flight Simulator for Advanced Aircraft (FSAA). During this practice period, the subject evaluated the simulation in the light of his earlier experience and judged it to be representative of the AWJSRA despite obvious differences in displays and controls.

A typical experimental session consisted of several fixed base practice runs with and without SAS, followed by the experimental runs, usually moving base first. Pilot commentary during or following the run was noted by the experimenter.

PERFORMANCE DATA AND CORRELATES

The standard deviation data are summarized in Table B-1. Note that the airplane motion variable data refer to computed variables, not cab motions. The subject voiced three reservations regarding the simulation, all of which would affect his performance, particularly in the lateral/directional control tasks:

- <u>Lateral Drift</u> — There was a tendency of the simulated airplane to drift left, a fault apparently explained by random variations in the mean lateral wind disturbances. The pilot would tend to hold a crabbed attitude to counter this drift.

TABLE B-1. SUMMARY OF PHASE I PERFORMANCE DATA

VARIABLE (UNITS)	WITH SAS			WITHOUT SAS			REMARKS
	FB (N = 6)	MB (N = 7)	PERCENT	FB (N = 9)	MB (N = 9)	PERCENT	
σ_{δ_c} (cm)	2.92	2.71	−7.1	3.31	2.92	−11.9*	
σ_{δ_w} (rad)	0.120	0.131	9.0	0.183	0.173	−5.4	
σ_{δ_p} (cm)	0.302	0.485†	61.0*	0.674	0.835	24.0*	Lateral drift (?)
σ_p (mr/sec)	26.9	27.8	3.2	42.4	37.6	−11.5*	
σ_q (mr/sec)	28.1	26.0	−7.4	31.2	27.4	−12.3*	
σ_r (mr/sec)	13.8	18.0	30.3*	24.8	20.4	−17.6*	Lateral drift (?)
σ_φ (m)	33.7	25.0	−25.9*	49.7	34.4	−30.9*	
σ_θ (mr)	37.9	36.7	−3.2	41.2	36.2	−12.2*	
σ_ψ	30.6	37.7	23.4*	47.0	37.0	−21.2*	Lateral drift (?)
$\sigma_{\ddot{h}}$ (m/sec^2)	0.741	0.701	−5.4	0.747	0.714	−4.2	
$\sigma_{\dot{h}}$ (m/sec)	1.037	1.092	5.3	1.030	1.015	−1.4	
σ_{V_a} (m/sec)	1.470	1.440	−2.1	1.304	1.410‡	8.2	"Largely ignore airspeed"
$\sigma_{\epsilon_{GS}}$ (mr)	3.02	3.45	14.3	2.74	3.04	11.0	
$\sigma_{\epsilon_{LOC}}$ (mr)	4.64	6.29	35.8*	4.49‡	4.46	−0.6	Lateral drift (?)

*Variances differ significantly with 95% confidence (F test).

†N = 4; three points omitted which are radically larger than remaining points.

‡N = 8; one point omitted which is radically larger than remaining points.

- **Turn/Slip Indicator** — This was judged to be "too insensitive." (The sensitivity was increased by some 40% for Phase II.)

- Rudder Pedals — These were judged to be "overly sensitive." (The breakout forces and gradient were reduced for Phase II to make control about the zero position more precise.)

The attitude ball itself was known to be jerky in its yaw response although the pilot did not so indicate. In light of the Phase II results, this probably influenced the lateral performance in Phase I as well.

The individual data points also show considerable scatter although a slight learning trend is evident in the runs without SAS. The subject commented on being tired during the second experimental session, a factor reflected in the data — the second day's performance was generally worse than the first even though the experimental conditions were the same for much of the data.

On comparing the data with and without SAS (Table B-1), in most cases the performance measures are less with the SAS, the major exceptions being the glide slope and localizer errors. These also would be expected to be better with the SAS. The fact that they are not is attributed to differences in pilot set, fatigue, and so on — most of the SAS data were taken in the first two days, while the no-SAS data was taken on the last two days.

The most interesting comparison is between the FB and MB conditions. With SAS, the data of Table B-1 show significant differences between these conditions for 5 of the 14 variables, all lateral/directional variables*. But these differences may be more apparent than real. Note that three data points have been eliminated from averaged performance for δ_p, the rudder pedal deflection. If the corresponding data points are eliminated from all averages, then only the improvement in roll attitude performance (σ_φ) becomes significant. The results are therefore inconclusive, although the improvement in roll attitude control is judged significant despite the possible

*Throughout this discussion, the F test for equality of variances is used as noted in Table B-1. The number of degrees of freedom associated with each variable is estimated based on the apparent bandwidth of each process and the total run time (aggregate of all runs for a given set of conditions).

influences of the simulation faults noted above. The subject pilot, however, felt that there was no difference between the FB and MB conditions with SAS.

Without the SAS, the number of significant differences between the FB and MB conditions increases to eight variables out of fourteen, all of which have relatively large bandwidths. Both longitudinal and lateral directional tasks show improvement under MB conditions. The pilot, after some deliberation (the last four runs were made to aid him in crystalizing his impressions), decided that there might be some improvement, MB, but that the improvement, if it existed, was slight. These results are largely in accord with the pre-experimental predictions where only a small improvement with motion was expectsd (see Table B-2)*.

The analysis summary of Table B-2 suggests the speed control (STOL) technique to be most appropriate. However, the pilot commented to the effect that he controls altitude with attitude changes and "largely ignores" airspeed changes, controlling them when necessary with the thrust diverter. "Ignoring airspeed" generally meant that he flew slightly fast (by 1 to 1.5 m/s), thus lessening the backsidedness and making the CTOL technique more feasible.

However, both the SAS and the no-SAS data show a tendency for the glide slope performance to deteriorate. This is true despite a slight improvement in the altitude acceleration performance and suggests a shift in the dominant mode frequency with this frequency being lower in the moving base case. This result differs from the trend for the other performance variables as well as from expectations.

One possible explanation for this result is that the pilot may alter his control strategy in such a way as to avoid encountering the simulator limits. That is, motion inhibits the subject. The decreased dominant mode frequency, while it deteriorates overall performance, can reduce the simulator cab excursions because of the washout's attenuation. In the present example, this frequency would appear (comparing $\sigma_{\epsilon_{GS}}$ and $\sigma_{\dot{h}}$ with

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*This analysis drew heavily on an analysis of the longitudinal handling qualities of the AWJSRA performed in the course of a concurrent NASA contract, NAS2-6441, "Flight Director Displays and Stability Augmentation System for the Augmentor Wing Jet STOL Research Aircraft."

TABLE B-2. PRE-EXPERIMENTAL ANALYSIS SUMMARY

Attitude Control, $\theta \to \delta_c$	
Phugoid mode is easily damped at low to moderate levels of pilot gain. Pilot lead not critical to attitude control. **Motion Effects**: Since little lead is required, angular rate cues can benefit attitude loop closure characteristics to only a small extent and will have a correspondingly small effect on path control.	
Speed Control (STOL) Technique $u,\ \theta \to \delta_c,\ \dot{h} \to \nu$	Altitude Rate Control (CTOL) Technique $\dot{h},\ \theta \to \delta_c,\ u \to \nu$
Low gain in $\left.\frac{u}{\theta}\right\rvert_{\theta \to \delta_c}$ and $\left.\frac{\dot{h}}{\nu}\right\rvert_{\omega,\ \theta \to \delta_c}$ transfer functions but these loop closures are not critically dependent upon attitude loop closure characteristics. **Motion Effects**: $a_{z_p} \to \nu$ can only improve situation slightly because of low sensitivity.	Low gain in $\left.\frac{u}{\nu}\right\rvert_{\theta \to \delta_c}$, however $u \to \nu$ closure puts vehicle on "front side". $\dot{h} \to \left.\theta\right\rvert_{\substack{\theta \to \delta_c \\ u \to \nu}}$ closure sensitive to short period damping, therefore more dependent on attitude loop closure. **Motion Effects**: $a_{z_p} \to \theta$ limited by short period damping, therefore of even less benefit.
Summary: STOL technique best unless pilot flies faster, thus reducing backsidedness of airplane, or ignores large attitude changes required for path control. Motion cues can improve attitude control but will have little effect on path control. Vertical acceleration cues of small utility.	

proper allowance for range) to be below the washout's break frequency of 0.5 rad/sec. Examination of strip chart recordings of the lateral and longitudinal cab position commands suggest that more encounters with the simulator limits would have occurred in the fixed base runs, particularly the lateral limits. Of course, more attention to the lateral task, moving base (or just the distraction of the motion, noise, and vibration) diverts attention from the longitudinal task. In short, the pilot may be flying the simulator instead of the airplane.

A second possible explanation of the performance trend may be associated with the scaling of the ILS needles. Consider the glide slope error: The scaling is such that the rms error (Table B-1) corresponds to an angular error at the pilot's eye of about 1.7 milliradians. Taking the dominant frequency (estimated by comparing $\sigma_{\dot{h}}$ to $\sigma_{\epsilon_{GS}}$, Table B-1, as 0.3 rad/sec implies an rms angular rate at the pilot's eye of about 0.5 milliradians/sec. This implies (based upon interpreted angular velocity threshold data quoted in Ref. 10) recognition times on the order of 4 sec. The rms glide slope error also implies rms vertical excursions of 3.36 to 4.27 m at the fixed effective range used for the ILS indicator. It is not hard to see that the vertical stops will be encountered occasionally, even with the motion attenuation used in these experiments.

A similar analysis for the localizer error reveals an rms amplitude at the pilot's eye of 1.3 milliradians. The dominant frequency is estimated to be about 0.3 rad/sec, suggesting an angular rate at the pilot's eye of approximately 0.4 milliradians/sec. The recognition time is even longer than for vertical errors. The computed rms lateral excursions of 7.95 to 10.98 m suggest, a) relatively more frequent limit exceedances plus b) dominant frequencies below 0.5 rad/sec, the washout break frequency to reduce the motion amplitude still further — there is no $\dot{y}$ data from which to estimate the dominant mode frequency).

The foregoing suggests that the motions of the ILS indicators are close to the pilot's threshold for detecting such motion. This would imply that the control precision achieved is limited by these thresholds. If so, then the simulator motion may act to increase these thresholds, with the result that performance deteriorates in the moving base condition.

Another factor affecting all the performance data is the magnitude of the motions in the experiment relative to the pilot's effective threshold. The magnitude of the angular rates sensed by the pilot (ignoring residual tilt rates, but including the motion attenuation by half) are typically a factor of three under his presumed angular rate thresholds, per Ref. 1 (see Table B-3). The sensed linear acceleration, $0.5\ddot{h}$, in the altitude control task is at an rms level near 0.035 g. The pilot felt this acceleration level to be barely detectable. (Lateral and longitudinal accelerations were not measured.) The experimental situation apparently is one where even though the angular rates are perhaps too low to be adequately sensed, the linear excursions are large enough to cause simulator limiting during a significant number of runs.

TABLE B-3. RMS ANGULAR MOTION RATES* IN PHASE I EXPERIMENT

	WITH SAS	NO SAS	THRESHOLD (Ref. 1)
Pitch	13.1	13.8	45.4
Yaw	9.1	10.3	19.2
Roll	13.8	18.9	55.9

SUMMARY

The Phase I experimentation was intended to prove out an experimental concept for the Phase II experiments and to provide some initial experimental data on motion effects. The results discussed above indicate the possible existence of threshold effects evident in both the visual and motion cues. These effects confound the data obtained in the Phase I experiment. On the other hand the data indicate some motion sensitivity — at least to the angular rates — in agreement with expectations. The pilot's

*In mr/sec. These figures are half those given in Table B-1, i.e., they do not include the effects of residual tilt or washout, but do include attenuation by half.

precision of attitude control in the simulated airplane is improved with the presence of motion cues.

With regard to the linear motion cues, the Phase I data do not shed much light. The motion differences are primarily in the angular degrees of freedom, and while the vertical accelerations are reduced under moving base conditions, it can be argued that the improved control is due to a change in "strategy", that is, to avoid hitting the travel limits, as much as due to the presence of the vertical acceleration cues. This strategy is one where the outer loop crossover frequencies are lower which increases the error but reduces the simulator excursions because of the attenuation of the motion washout.

The amplitude of the motion cues was not varied in this experiment (except between FB and MB), as a means of ascertaining motion threshold effects. However, the motion amplitudes observed indicate that these effects could be present. In fact, the significant improvement in attitude control, moving base, suggests that the effective angular motion thresholds for this task (and subject) are lower than heretofore supposed (i.e., in Ref. 1) because of the low rms angular rates relative to this presupposed threshold, particularly in pitch and roll.

These results suggested that the Phase II experiments be designed, at least in part, to answer some of the questions raised. The IFR experiment in particular (Section III) was intended to determine if visual velocity threshold effects and changes in piloting "strategy" influenced the Phase I results. The VFR experimental configuration (Section IV) was influenced by the desire to increase the angular rates and linear accelerations without violating the simulator limits. And, of course, the single axis tracking experiment (Section II) was motivated by the desire for an unambiguous answer to the question of whether or not linear acceleration cues could be effectively utilized in a tracking task.

APPENDIX C

PHASE II SUPPLEMENTARY DATA

This appendix contains supporting data to the discussions in the main text. A run by run listing of all the data for each of the three experiments in not included — the computer printouts are quite long, and by themselves, not especially illuminating. Rather, certain averaged data from these experiments are presented. In the case of the standard deviations of the various motion variables, this tends to weight episodes of poorer performance more heavily. On the other hand, there is no good reason for discarding such data in most instances.

LEARNING TRENDS IN THE SINGLE-AXIS TRACKING TASK

The results and conclusions drawn in Section II are based upon interpretation of averaged data where the average is taken over the last two or three runs for a particular configuration and subject. These runs were made at a higher controlled element gain (K_c = 3.96 sec^{-2}) than the earlier data (K_c = 2.64 sec^{-2}) and represent performance closer to asymptotic values and optimum gains than the earlier data. To place these results in perspective, it is appropriate to consider the learning trends exhibited in the experimental results.

The controlled element gain was initially selected by EF in fixed base trial runs where the lag time constant was 0.1 sec. This later proved sub-optimum when increased training on the part of both subjects plus increased lag (to 1.0 sec) resulted in using virtually full controller travel in each of the tasks. The last two or three runs were made for the express purpose of evaluating the 50% higher gain and investigating the effect of cab position on the simulator's tower. Both pilots commented favorably on the gain increase. Even so, the gain was sub-optimum to judge by the subject's control activity. It frequently consisted of stop-to-stop deflections.

The comgined effects of learning and the gain increase are illustrated in Fig. C-1 for the centerstick tasks for both subjects. (Earlier runs than

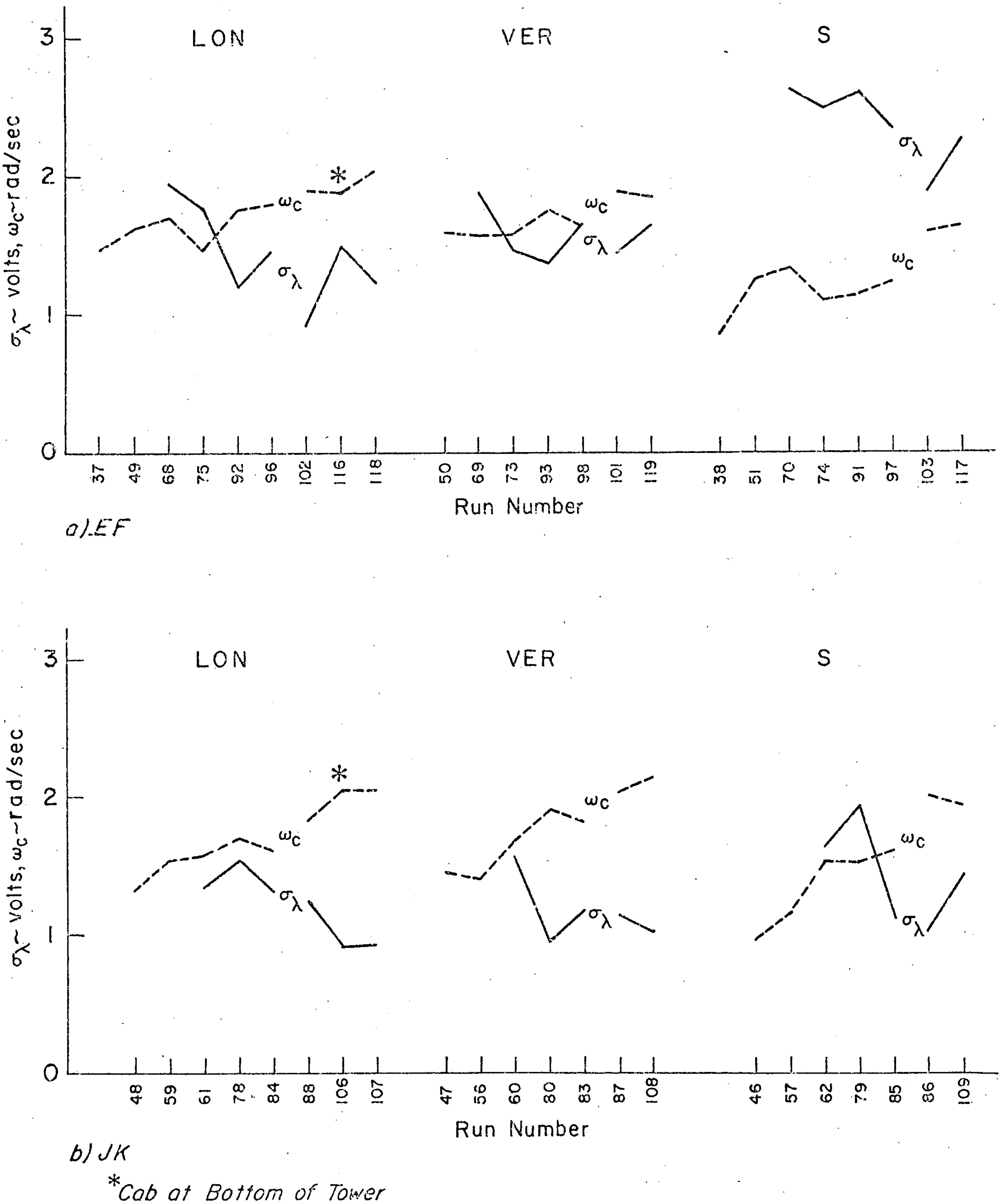
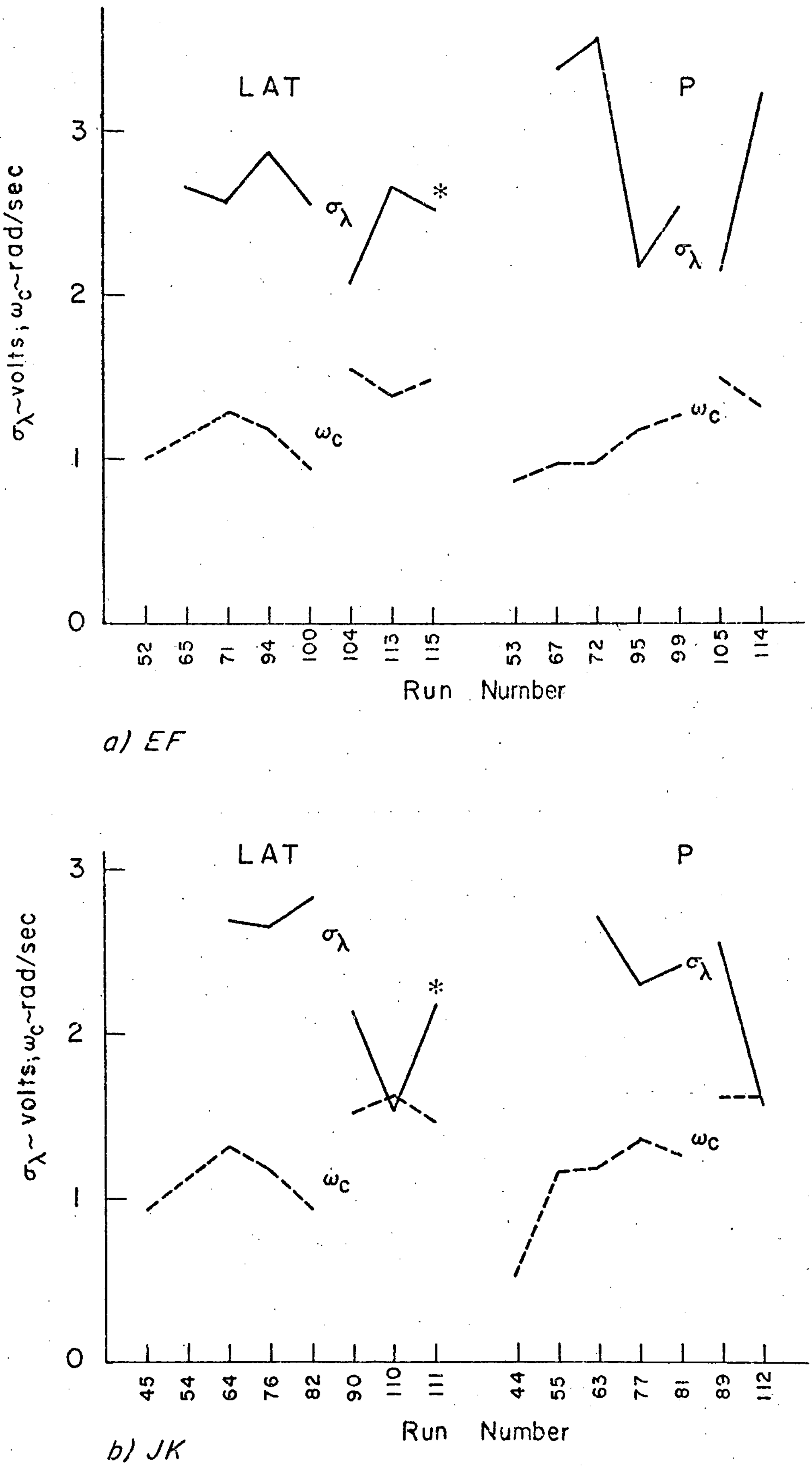


Figure C-1. Learning Trend Data, Centerstick Tasks those noted here were made with lower lag time constants than the 1.0 sec pertinent to these data.) The gap in each of the plots of rms error and crossover frequency, ω_c (determined from the describing function measurements), separate the low K_c data on the left from the higher K_c data on the right. A learning trend is clearly evident in the ω_c data at low K_c for both subjects. The last two or three points show a continuation of the trend, however the improvement can also be ascribed to the increased gain. The trend is less obvious in the rms data because of fewer runs and increased scatter in the data points. Nevertheless it is clear that the later performance represents an improvement over the earlier.

Figure C-2 shows the equivalent data for the pedal tasks. The same trends, albeit with more scatter in σ_λ, are exhibited as for the center-stick tasks.

The asterisks in both figures identify runs made with the cab at the bottom of the tower. In the LON configuration, neither pilot noted any difference in the motion sensation. But in the IAT configuration, EF noted "less jerky" motion at the bottom of the tower, while JK thought the motion seemed "delayed" in this position. The implication is clear — lateral simulator motion contains extraneous accelerations, perhaps associated with the tower's torsional dynamics — the cab center of mass is forward of the tower centerline. However the limited data available are insufficient to demonstrate a performance difference. These data points were therefore lumped in with the rest.

The open-loop describing function data for the four runs preceding the gain change and the two or three runs following it are given in Table C-1. The averaging was accomplished by treating the data as coming from one long run. For example, the raw measurements of the real and imaginary parts of the measured error-to-input describing function as measured by the describing function analyzer were averaged and the results used to determine the averaged open-loop describing function. The data trends for the earlier data are the same as for the later with one exception: For JK, the IAT configuration exhibits poorer performance than P when $K_c = 2.64\ \text{sec}^{-2}$; the reverse for $K_c = 3.96\ \text{sec}^{-2}$. The data trends are therefore relatively insensitive to learning effects — an important factor in evaluating the validity of the trends exhibited.



*Cab at Bottom of Tower

Figure C-2. Learning Trend Data, Pedal Tasks

TABLE C-1

AVERAGED DATA SUMMARY, SINGLE-AXIS TRACKING EXPERIMENT

PILOT	K_c (sec^{-2})	CONFIG.	NUMBER OF RUNS	ω_c (rad/sec)	k_m (dB)	φ_m (deg)	$\varphi(6.283)$ (deg)	σ_γ (volts)
EF	2.64	S	4	1.30	4.7	27	−344	2.52
		LON	4	1.68	6.0	28	−241	1.62
		VER	4	1.65	5.6	26	−253	1.59
		P	4	1.15	5.2	29	−362	2.96
		LAT	4	1.22	6.4	28	−279	2.67
	3.96	S	2	1.62	2.6	16	−351	2.10
		LON	3	1.93	6.0	28	−225	1.25
		VER	2	1.86	4.2	24	−229	1.55
		P	2	1.35	3.7	22	−390	2.72
		LAT	3	1.45	4.8	24	−250	2.45
JK	2.64	S	4	1.47	4.3	23	−339	1.64*
		LON	4	1.61	5.1	26	−283	1.40*
		VER	4	1.70	5.0	22	−259	1.27*
		P	4	1.25	7.6	29	−311	2.47*
		LAT	4	1.17	8.4	28	−275	2.72*
	3.96	S	2	1.98	1.6	10	−300	1.26
		VER	2	2.10	3.8	16	−218	1.10
		P	2	1.61	3.6	18	−302	2.14
		LAT	3	1.53	4.9	18	−257	1.96

*These error data are for 3 runs only, unlike the describing function data.

Another factor lending credance to these trends is the relatively small run-to-run scatter in the describing function data where that data counts for most — in the region near crossover. In this frequency region, the signal power is greatest and the measured describing function most accurate. At the middle frequency used in these measurements ($\omega = 1.257$ rad/sec), generally somewhat below crossover, the range (smallest to largest value) of the Y_pY_c gain data is typically about 3 dB for EF, 7 dB for JK; of the phase data, about 10 deg for EF, 15 deg for JK. This is borne out by the plotted data of Figs. C-1 and C-2 — the range of ω_c is somewhat larger for JK than for EF.

The accuracy falls off somewhat at the highest frequency, $\omega = 6.283$ rad/sec. Here the gain range is typically about 10 dB for EF, 15 dB for JK; the range in phase measurements, about 60 deg for EF (smaller for the center-stick tasks, larger for the pedal tasks) and 75 deg for JK — most of the range taken up by the learning trend (less gain and more phase lag for the earlier runs). Even so, the averaged phase data listed for this frequency in Table C-1 is felt to be indicative of the motion effects.

At the two lowest frequencies, the accuracy of the describing function measurements was extremely poor. This is because error power at these frequencies is low — the second derivative of the error (that signal actually measured by the DFA) is lower yet. The range in the run-to-run measurements of Y_pY_c at these frequencies was enormous — exceeding 20 dB of gain and 300 deg of phase in some instances. As a result, <u>all</u> the data (6 or 7 runs) was averaged at these two frequencies in an effort to gain a better estimate of Y_pY_c at these frequencies. Even so, the data in the main text (Figs. 4 and 5) at these frequencies is felt to be unreliable, particularly for the pedal tasks.

PERFORMANCE DATA TRENDS IN THE IFR TRACKING TASK

As pointed out in Section III there is considerable scatter in the performance data for a variety of reasons. Consequently, there is a problem in drawing results from these data: Should all runs be considered, or only the last four where the subject is closer to an asymptotic performance level and it is known that the input disturbance generator is working properly? Another option is to extrapolate the data to presumed asymptotic performance levels and compare these — a process which can be faulted as too subjective.

The point of view adapted is to regard those trends (variations in the data between experimental configurations) valid which are established, for each experimental configuration, by both the grand average data (all runs for a configuration) and an average over the last four runs. Tables C-2 and C-3 list these averages for most of the performance parameters.

In all cases, the data show that the pilot flies slightly fast (by 1.1 to 1.7 m/sec) with the thrust deflected slightly aft of the desired trim condition (by 0.05 to 0.10 rad). This tends to improve the altitude responses of the aircraft. The pilot, in making his tradeoff between altitude, lineup, and airspeed errors chooses an airspeed slightly high as being the best compromise.

To assess the effects of motion cues on the longitudinal task (the lateral task trends are regarded as unreliable because of the sticking attitude ball in yaw as noted in Section III), the MB and MB − L configurations are compared with FB. Examination of Tables C-2 and C-3 shows σ_q, $\sigma_{\ddot{h}}$, $\sigma_{\dot{h}}$, $\sigma_{\hat{z}}$ and the pitch attitude control task "bandwidth", σ_q/σ_θ, all decreasing with the addition of the longitudinal task motion cues. But the validity criterion adopted does not permit any conclusion to be drawn concerning longitudinal task performance as indicated by $\sigma_{\epsilon_{GS}}$. Consequently the overall altitude performance is judged essentially invariant with the presence or absence of longitudinal task motion cues.

A similar assessment of the effects of the presence or absence of lateral motion (comparing the MB and MB − L; the MB + N and MB + N − L configurations) shows a slight improvement in the altitude error, $\sigma_{\epsilon_{GS}}$, and the altitude task "bandwidth", $\sigma_{\dot{h}}/\sigma_h$, when the lateral motion is removed — $\sigma_{\epsilon_{GS}}$ decreases and $\sigma_{\dot{h}}/\sigma_h$ increases for the −L configurations.

The effect of doubling the ILS needle sensitivity is manifested in many more variables. Comparing MB vs. MB + N, and MB − L vs. MB + N − L shows changes for most of the dependent variables — σ_{δ_c}, σ_q, $\sigma_{\ddot{h}}$, $\sigma_{\dot{h}}$, and $\sigma_{\dot{h}}/\sigma_h$

TABLE C-2

PERFORMANCE DATA SUMMARY, IFR TRACKING EXPERIMENT

CONFIGURATION		FB	MB	MB + N	MB − L	MB + N − L
NUMBER OF RUNS		8	9	9	7	8
TRIM CONDITIONS						
$\overline{V}_a$	m/sec	32.2	32.2	31.7	32.2	31.6
$\overline{\delta}_{th}$	rad	0.33	0.33	0.32	0.33	0.33
$\overline{\nu}$	rad	1.44	1.48	1.39	1.47	1.44
$\overline{V}_N$	m/sec	0.29	0.32	0.29	0.30	0.31
$\overline{p}_N$	mr/sec	−1.17	−1.32	−1.28	−1.36	−1.21
LONGITUDINAL TASK PERFORMANCE						
σ_{δ_c}	cm	2.29	1.95	2.49	1.90	2.47
σ_q	mr/sec	22.6	18.1	23.5	17.5	22.4
σ_θ	mr	35.7	38.1	41.4	31.7	44.8
σ_q/σ_θ	sec^{-1}	0.63	0.48	0.57	0.55	0.50
$\sigma_{\ddot{h}}$	m/sec^2	0.49	0.43	0.52	0.43	0.52
$\sigma_{\dot{h}}$	m/sec	0.86	0.80	0.93	0.77	0.94
$\sigma_{\epsilon_{GS}}$	mr	3.52	3.22	2.76	3.02	2.71
$\sigma_{\dot{h}}/\sigma_h$	sec^{-1}	0.195	0.195	0.267	0.202	0.273
LATERAL/DIRECTIONAL TASK PERFORMANCE						
σ_{δ_p}	cm	0.73	0.96	1.06	0.91	1.10
σ_r	mr/sec	25.6	25.6	25.5	26.5	29.9
σ_ψ	mr	63.2	61.1	63.9	55.5	63.7
σ_r/σ_ψ	sec^{-1}	0.41	0.42	0.40	0.48	0.47
σ_{δ_w}	rad	0.20	0.21	0.20	0.21	0.23
σ_p	mr/sec	39.3	41.1	36.2	40.3	48.4
σ_φ	mr	57.0	54.7	54.7	56.7	65.9
σ_p/σ_φ	sec^{-1}	0.69	0.75	0.66	0.71	0.73
$\sigma_{\dot{y}}$	m/sec	1.50	1.72	1.77	1.60	1.74
$\sigma_{\epsilon_{LOC}}$	mr	9.39	9.42	6.85	6.69	6.27
$\sigma_{\dot{y}}/\sigma_y$	sec^{-1}	0.091	0.104	0.148	0.136	0.158
COMMANDED SIMULATOR MOTIONS						
$\sigma_{\hat{x}}$	m	0.25	0.29	0.32	0.23	0.31
$\sigma_{\hat{y}}$	m	0.66	0.60	0.68	0.59	0.74
$\sigma_{\hat{z}}$	m	0.44	0.41	0.51	0.40	0.52

TABLE C-3

PERFORMANCE DATA, IFR TRACKING EXPERIMENT
(LAST FOUR RUNS, EACH CONFIGURATION)

CONFIGURATION		FB	MB	MB + N	MB − L	MB + N − L
NUMBER OF RUNS		—— LAST 4 RUNS ——				
TRIM CONDITIONS						
$\bar{V}_a$	m/sec	31.7	31.3	31.6	31.4	31.6
$\bar{\delta}_{th}$	rad	0.33	0.33	0.33	0.33	0.33
ν	rad	1.46	1.48	1.43	1.45	1.45
$\bar{V}_N$	m/sec	0.23	0.26	0.27	0.23	0.26
$\bar{p}_N$	mr/sec	−1.53	−1.75	−1.63	−1.70	−1.54
LONGITUDINAL TASK PERFORMANCE						
σ_{δ_c}	cm	1.80	1.85	2.26	1.88	2.03
σ_q	mr/sec	17.4	16.5	21.7	16.9	19.6
σ_θ	mr	30.9	39.5	36.7	32.6	40.6
σ_q/σ_θ	sec^{-1}	0.56	0.42	0.59	0.52	0.48
$\sigma_{\ddot{h}}$	m/sec^2	0.43	0.40	0.50	0.42	0.50
$\sigma_{\dot{h}}$	m/sec	0.72	0.69	0.89	0.70	0.89
$\sigma_{\epsilon_{GS}}$	mr	2.49	2.76	2.52	2.71	2.36
$\sigma_{\dot{h}}/\sigma_h$	sec^{-1}	0.230	0.199	0.278	0.206	0.299
LATERAL/DIRECTIONAL TASK PERFORMANCE						
σ_{δ_p}	cm	0.69	0.84	0.94	0.76	1.08
σ_r	mr/sec	24.1	24.6	23.2	22.7	29.9
σ_ψ	mr	67.3	59.8	58.9	56.0	66.3
σ_r/σ_ψ	sec^{-1}	0.36	0.41	0.39	0.41	0.45
σ_{δ_w}	rad	0.19	0.23	0.18	0.19	0.22
σ_p	mr/sec	36.8	43.3	33.5	35.3	47.6
σ_φ	mr	54.4	59.4	53.0	49.4	66.9
σ_p/σ_φ	sec^{-1}	0.68	0.73	0.63	0.72	0.71
$\sigma_{\dot{y}}$	m/sec	1.37	1.51	1.69	1.39	1.71
$\sigma_{\epsilon_{LOC}}$	mr	9.62	8.69	7.00	6.33	7.05
$\sigma_{\dot{y}}/\sigma_y$	sec^{-1}	0.081	0.099	0.138	0.125	0.138
COMMANDED SIMULATOR MOTIONS						
$\sigma_{\hat{x}}$	m	0.25	0.25	0.30	0.23	0.31
$\sigma_{\hat{y}}$	m	0.65	0.67	0.66	0.55	0.76
$\sigma_{\hat{z}}$	m	0.40	0.34	0.49	0.38	0.51

all increase when the sensitivity is increased; $\sigma_{\epsilon_{GS}}$ decreases, i.e., the altitude performance improves. The simulator motions, $\sigma_{\hat{x}}$ and $\sigma_{\hat{z}}$, also increase slightly. Even some of the lateral/directional variables are affected — σ_{δ_p}, $\sigma_{\dot{y}}$, and $\sigma_{\dot{y}}/\sigma_y$ all increase in the +N configurations. The effect of increasing the ILS needle sensitivity is judged relatively substantial, in view of its effects on most of the motion variables.

PERFORMANCE DATA IN THE VFR TRACKING EXPERIMENT

The last six to eight runs for each configuration and subject provide the data listed in Tables C-4, C-5, and (for the altitude control task describing functions) C-6 which comprize the quantitative results of the VFR tracking experiment discussed in Section IV of the main text. In all cases, the data listed assumes one long run, for example:

$$\sigma_{avg} = \sqrt{\frac{1}{N}\sum_{i=1}^{N}\sigma_i^2} \qquad \text{(C-1)}$$

The performance is felt to be typical of well trained behavior — each subject had upwards of one hundred prior runs on all configurations. However these earlier data are not strictly comparable with the later because of differences in the disturbances used.

It is interesting to compare these data with the individual subjects' perceptual thresholds as given in Table C-7 and, with modifications, Table C-8. The Table C-4 and C-5 data for standard deviation of body axis rates are modified to take account of motion washout scheme scale factor in Table C-9. Comparing Tables C-8 and C-9 reveals the following:

1. EF's roll rates are generally [exceptions: Configuration Nos. 1 and 2 (no $\hat{\ddot{z}}$)] somewhat greater than JK's, but his equivalent angular rate threshold (Table C-8) is slightly less.

2. EF's pitch rates are generally [exception: Configuration No. 4] less than JK's, but his threshold is greater by a substantial (3 to 1) margin.

3. EF's yaw rates are less than JK's, but his threshold is greater, by almost 2 to 1.

TABLE C-4

PERFORMANCE DATA, VFR TRACKING EXPERIMENT, SUBJECT EF

CONFIGURATION		FB	1	2	3	4	2 (no $\ddot{z}$)	2 (no θ, $\ddot{x}$)
NUMBER OF RUNS		6	7	5	6	7	6	7
TRIM CONDITIONS								
$\bar{V}_a$	m/sec	31.2	31.6	31.5	31.3	31.3	32.0	31.0
$\bar{\delta}_{th}$	rad	0.52	0.52	0.52	0.52	0.52	0.52	0.52
$\bar{\nu}$	rad	1.27	1.27	1.27	1.24	1.26	1.29	1.24
$\bar{V}_N$	m/sec	0.25	0.36	0.27	0.30	0.24	0.25	0.29
$\bar{p}_N$	mr/sec	−1.41	−1.16	−1.58	−1.36	−1.55	−1.07	−1.41
LONGITUDINAL TASK PERFORMANCE								
σ_{δ_c}	cm	1.83	1.63	1.72	2.01	2.55	1.84	2.24
σ_q	mr/sec	18.0	19.3	17.0	18.9	22.5	18.8	21.2
σ_θ	mr	24.2	27.4	24.2	25.2	28.8	31.1	25.8
σ_q/σ_θ	sec^{-1}	0.74	0.70	0.70	0.75	0.78	0.61	0.82
$\sigma_{\ddot{h}}$	m/sec^2	0.63	0.70	0.65	0.68	0.83	0.76	0.73
$\sigma_{\dot{h}}$	m/sec	0.63	0.66	0.63	0.62	0.73	0.79	0.69
σ_h	m	2.63	2.47	2.36	2.67	3.16	3.65	2.33
$\sigma_{\dot{h}}/\sigma_h$	sec^{-1}	0.24	0.27	0.27	0.23	0.23	0.22	0.30
LATERAL/DIRECTIONAL TASK PERFORMANCE								
σ_{δ_p}	cm	0.20	0.24	0.31	0.24	0.26	0.22	0.26
σ_r	mr/sec	13.2	13.4	12.4	13.2	14.2	12.4	12.4
σ_ψ	mr	31.8	30.1	28.2	28.8	28.3	30.9	28.9
σ_r/σ_ψ	sec^{-1}	0.42	0.45	0.44	0.46	0.50	0.40	0.43
σ_{δ_w}	rad	0.20	0.18	0.16	0.19	0.23	0.14	0.17
σ_p	mr/sec	44.6	44.0	38.3	44.5	57.4	36.1	40.6
σ_φ	mr	41.6	45.2	52.4	52.2	61.2	47.2	52.4
σ_p/σ_φ	sec^{-1}	1.07	0.98	0.76	0.85	0.94	0.76	0.78
$\sigma_{\dot{y}}$	m/sec	0.98	0.95	1.16	1.04	1.09	1.02	1.11
σ_y	m	4.05	4.12	3.48	3.25	4.01	3.43	3.54
$\sigma_{\dot{y}}/\sigma_y$	sec^{-1}	0.24	0.23	0.33	0.32	0.27	0.30	0.31
COMMANDED SIMULATOR MOTIONS								
$\sigma_{\hat{x}}$	m	—	0.63	0.44	0.26	0.16	0.54	—
$\sigma_{\hat{y}}$	m	—	0.54	0.61	0.55	0.54	0.58	0.66
$\sigma_{\hat{z}}$	m	—	0.73	0.69	0.41	0.29	—	0.77

TABLE C-5

PERFORMANCE DATA, VFR TRACKING EXPERIMENT, SUBJECT JK

CONFIGURATION		FB	1	2	3	4	2 (no $\ddot{z}$)	2 (no θ, $\ddot{x}$)
NUMBER OF RUNS		5	6	5	6	6	5	5
TRIM CONDITIONS								
$\bar{V}_a$	m/sec	32.0	32.2	32.5	32.3	31.8	32.2	31.9
$\bar{\delta}_{th}$	rad	0.51	0.51	0.51	0.51	0.51	0.51	0.51
$\bar{\nu}$	rad	1.23	1.22	1.28	1.29	1.21	1.22	1.23
$\bar{V}_N$	m/sec	−0.01	−0.09	−0.02	−0.03	−0.28	−0.05	−0.01
$\bar{p}_N$	mr/sec	−2.01	−2.32	−2.16	−2.10	−1.97	−2.18	−1.87
LONGITUDINAL TASK PERFORMANCE								
σ_{δ_c}	cm	3.64	2.87	2.86	2.70	2.71	2.83	3.34
σ_q	mr/sec	29.0	22.7	24.3	22.2	21.9	24.1	25.8
σ_θ	mr	29.1	26.8	26.8	25.6	21.9	29.8	27.2
σ_q/σ_θ	sec^{-1}	1.00	0.85	0.91	0.87	1.00	0.81	0.95
$\sigma_{\ddot{h}}$	m/sec^2	0.97	0.76	0.98	0.82	0.76	0.86	0.89
$\sigma_{\dot{h}}$	m/sec	0.54	0.53	0.61	0.54	0.53	0.57	0.60
σ_h	m	1.72	1.95	1.76	1.89	1.75	1.73	2.04
$\sigma_{\dot{h}}/\sigma_h$	sec^{-1}	0.32	0.27	0.35	0.28	0.30	0.33	0.29
LATERAL/DIRECTIONAL TASK PERFORMANCE								
σ_{δ_p}	cm	0.54	0.68	0.53	0.56	0.61	0.62	0.62
σ_r	mr/sec	17.1	18.2	15.5	17.7	19.2	15.8	15.8
σ_ψ	mr	36.4	34.3	36.1	37.4	44.7	34.4	36.0
σ_r/σ_ψ	sec^{-1}	0.48	0.53	0.43	0.48	0.43	0.46	0.44
σ_{δ_w}	rad	0.22	0.22	0.17	0.18	0.20	0.17	0.17
σ_p	mr/sec	48.1	45.9	37.2	41.8	47.1	37.4	35.2
σ_φ	mr	38.9	44.4	39.9	49.0	52.2	40.5	37.3
σ_p/σ_φ	sec^{-1}	1.22	1.03	0.94	0.89	0.90	0.93	0.94
$\sigma_{\dot{y}}$	m/sec	0.96	1.17	1.18	1.34	1.19	1.14	1.18
σ_y	m	4.04	3.59	3.67	3.30	3.42	3.07	3.37
$\sigma_{\dot{y}}/\sigma_y$	sec^{-1}	0.24	0.33	0.32	0.41	0.35	0.37	0.35
COMMANDED SIMULATOR MOTIONS								
$\sigma_{\hat{x}}$	m	—	0.59	0.46	0.23	0.13	0.54	—
$\sigma_{\hat{y}}$	m	—	0.55	0.51	0.55	0.49	0.51	0.48
$\sigma_{\hat{z}}$	m	—	0.54	0.64	0.33	0.22	—	0.62

TABLE C-6

DESCRIBING FUNCTION DATA, VFR TRACKING EXPERIMENT

a) SUBJECT EF

			MEASUREMENT FREQUENCY (rad/sec)					
CONFIG.	N	ρ^2	0.188	0.503	1.257	3.016	6.283	
FB	6	0.244	−5.31 −67.9	−4.61 −134.3	−14.98 −249.7	−18.47 −408.9	−34.19 −723.6	dB deg
1	6	0.252	−1.03 −77.2	−5.56 −132.7	−15.84 −217.1	−35.74 −290.6	−35.14 −479.2	
2	6	0.219	2.10 −83.6	−3.37 −136.2	−11.48 −200.6	−18.73 −365.0	−36.02 −692.7	
3	5	0.164	0.40 −64.4	−4.01 −138.3	−14.69 −216.4	−22.77 −363.1	−33.16 −422.1	
4	7	0.216	−0.63 −99.6	−4.59 −149.5	−12.66 −197.5	−36.41 −305.5	−30.64 −403.7	
2 (no $\hat{\ddot{z}}$)	6	0.217	−5.65 −102.6	−2.89 −149.5	−10.66 −257.8	−31.04 −505.0	−33.54 −709.6	
2 (no $\hat{\theta},\hat{\ddot{x}}$)	6	0.288	−1.31 −63.5	−3.77 −144.6	−15.79 −185.1	−15.80 −388.6	−30.75 −496.6	dB deg

b) SUBJECT JK

			MEASUREMENT FREQUENCY (rad/sec)					
CONFIG.	N	ρ^2	0.188	0.503	1.257	3.016	6.283	
FB	7	0.399	−0.73 −85.3	0.37 −121.8	−6.85 −188.1	−8.58 −308.0	−29.91 −542.5	dB deg
1	8	0.335	4.20 −156.0	−1.96 −119.3	−8.99 −168.2	−13.66 −291.1	−27.87 −426.7	
2	7	0.396	3.16 −98.4	−2.09 −120.0	−5.29 −176.6	−20.83 −303.4	−25.14 −444.7	
3	7	0.344	6.37 −78.4	−1.16 −121.5	−6.68 −178.0	−26.52 −372.2	−29.88 −666.9	
4	7	0.246	6.49 −72.3	−1.89 −115.2	−9.11 −180.1	−19.38 −378.0	−31.90 −718.7	
2 (no $\hat{\ddot{z}}$)	7	0.245	5.49 −75.8	−0.77 −122.7	−7.98 −188.8	−16.12 −367.4	−31.48 −527.3	
2 (no $\hat{\theta},\hat{\ddot{x}}$)	7	0.249	4.17 −83.8	−2.57 −122.4	−8.39 −170.8	−25.23 −362.6	−25.97 −433.8	dB deg

TABLE C-7. SUBJECT THRESHOLDS FOR PERCEPTION OF ROTATION*

SUBJECT	ROLL	PITCH	YAW
EF	8.55	11.86	4.71
JK	10.12	3.66	2.79

TABLE C-8. EQUIVALENT SUBJECT VELOCITY THRESHOLDS†

SUBJECT	ROLL	PITCH	YAW
EF	55.5	62.9	37.7
JK	65.6	19.4	22.4

TABLE C-9. SIMULATOR CAB RATES‡

CONFIGURATION		FB	1	2	3	4	2 (no $\ddot{z}$)	2 (no θ, $\ddot{x}$)
EF	$\sigma_{\hat{p}}$	—	15.4	19.2	33.4	57.4	18.1	20.3
	$\sigma_{\hat{q}}$	—	9.7	17.0	18.9	22.5	18.8	—
	$\sigma_{\hat{r}}$	—	4.7	6.2	9.9	14.2	6.2	6.2
JK	$\sigma_{\hat{p}}$	—	16.1	18.6	31.3	47.1	18.7	17.6
	$\sigma_{\hat{q}}$	—	11.4	24.3	22.2	21.9	24.1	—
	$\sigma_{\hat{r}}$	—	6.4	7.8	13.3	19.2	7.9	7.9

*In mr/sec^2, from Ref. 14.

†In mr/sec. Assumes T_{roll} = 6.5 sec, T_{pitch} = 5.3 sec, and T_{yaw} = 8.0 sec per Ref. 1 where $p_{threshold} \doteq T_{roll}\,\dot{p}_{threshold}$, and similarly for other axes.

‡In mr/sec. Neglects residual tilt and rate washout effects, that is, includes only the effects of motion scale factor.

It can be concluded that the data do not establish any correlation between the subjects' ability to detect angular rates and the rates actually measured. Further, the angular rates are about the same or less than the supposed thresholds. This suggests that the effective angular rate thresholds in the simulated task are less than the heretofore supposed thresholds of Table C-8. For example, in going from FB to 2, the computed roll rates and "bandwidths" (σ_p/σ_q) decrease significantly, indicating the influence of motion; yet the cab roll rates ($\sigma_{\hat{p}}$) are approximately one-third the subject thresholds.

APPENDIX D

AD HOC EXPERIMENT

During the course of the Phase II experiments, a need developed for establishing how much linear travel should be designed into an all-axis simulator for simulating flight with a STOL aircraft. A closely related question is to ask how much residual tilt can be tolerated for a given maximum linear travel. To analyze this question very briefly, it was decided to use the AWJSRA simulation upon completion of the Phase II experiments, perform a longitudinal maneuvering task, and rely on pilot commentary as the experimental measurements. The specific task was to fly the AWJSRA in level flight at 274 m altitude under VFR conditions, intercept the desired glide path ($\gamma = -0.131$ rad) as indicated by the ILS needles, fly down the glide path until a flare altitude was reached, and then flare the simulated aircraft and try to land it. At touchdown, the computation ceased. During this sequence of longitudinal task maneuvers, there were no disturbances, so that the pilots could concentrate on the motion sensations to which they were subjected.

As an initial experiment, the parameters of an uncoordinated washout were varied in several ways, using a single pilot subject whose extensive experience with motion simulators qualified him to make at least preliminary assessments. Preference for full motion amplitude was expressed early in these runs. The variations started off with an uncoordinated washout, then with alteration of some of the parameters was converted to a nearly coordinated situation; thereby affording comparison of the relative effects of the residual tilt in the two cases. By performing several iterations along this line a configuration was arrived at which was uncoordinated (at least in the mid frequency range) and which provided residual tilt sensations which were low enough in the maneuvers to be tolerated by the subject. The resulting configuration was used in the succeeding experimentation as a "baseline" case. There were three variations: first, deleting the longitudinal drive signal to the simulator; second, deleting that portion of the pitch drive signal ascribable to residual tilt; and third, a combination of the preceding two. These four experimental configurations are more fully documented in the next subsection of this appendix. The succeeding subsection describes the methodology, results, and conclusions.

WASHOUT CONFIGURATION

The uncoordinated washout scheme used in this experiment was developed in Refs. 12 and 13 and is illustrated (excluding the simulator compensation and motion limiting scheme) in Fig. D-1. In this scheme, as well as the scheme of Fig. A-6, small cab tilt angles are used to provide a low frequency portion of the translational accelerations (or specific forces) sensed in the simulator cab. In fact, the parameters of the lag filter in Fig. D-1 can be adjusted such that the system is coordinated with respect to input forces; but it is never coordinated with respect to input body axis rates.

For small angles, the simulator cab rates are given by:

$$\begin{bmatrix} \dot{\hat{\varphi}} \\ \dot{\hat{\theta}} \\ \dot{\hat{\psi}} \end{bmatrix} \doteq \frac{K_{\omega}(0)^2(1/T_{R_1})(1/T_{R_2})}{(1/\tau_{\omega})[\zeta,\omega](1/T'_{R_2})} \begin{bmatrix} p \\ q \\ r \end{bmatrix} + \frac{(K_S K_R/T_{R_1}T_{R_2})(0)}{[\zeta,\omega](1/T'_{R_2})} \begin{bmatrix} -a_{y_p} \\ a_{x_p} \\ 0 \end{bmatrix} \qquad \text{(D-1)}$$

where the second term represents the false rate cue attributable to residual tilt.

The cab translational accelerations are given by:

$$\begin{bmatrix} \ddot{\hat{x}} \\ \ddot{\hat{y}} \\ \ddot{\hat{z}} \end{bmatrix} \doteq \frac{K_a(0)^4}{[\zeta_{\ell},\ \omega_{\ell}][\zeta_n,\ \omega_n]} \begin{bmatrix} a_{x_p} \\ a_{y_p} \\ a_{z_p} \end{bmatrix} \qquad \text{(D-2)}$$

The amplitude response of this linear motion washout is shown in the sketch of Fig. D-2. It is fourth order because of the necessity of using the inertial washout to eliminate long term drifts in the final integration of the computed linear accelerations of the motion simulator cab.

The major objective in the initial experimentation was to arrive at a set of parameters for this scheme which, in the context of the maneuvering task being performed, would provide realistic amplitudes of acceleration

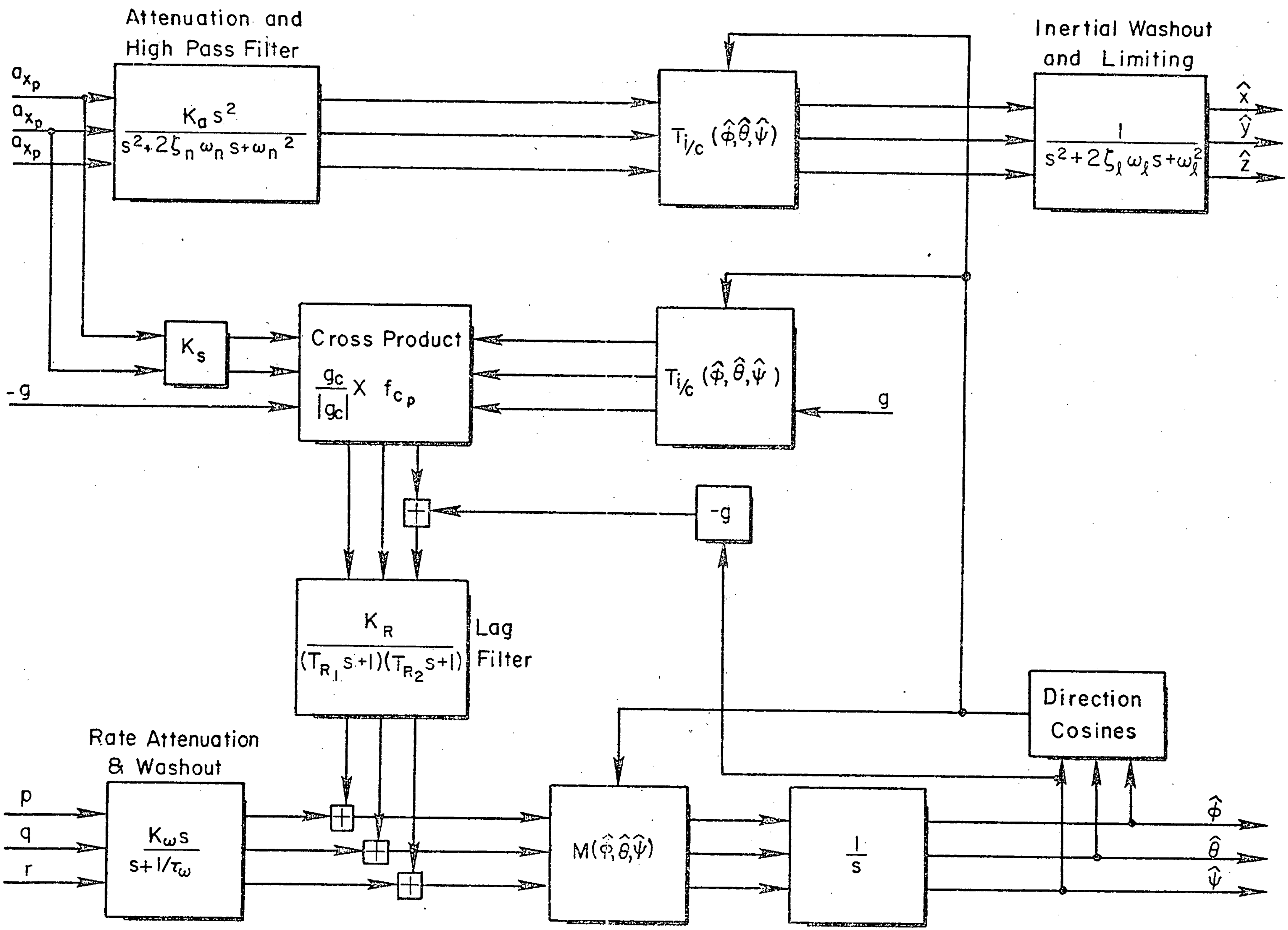


Figure D-1. Uncoordinated Washout Scheme

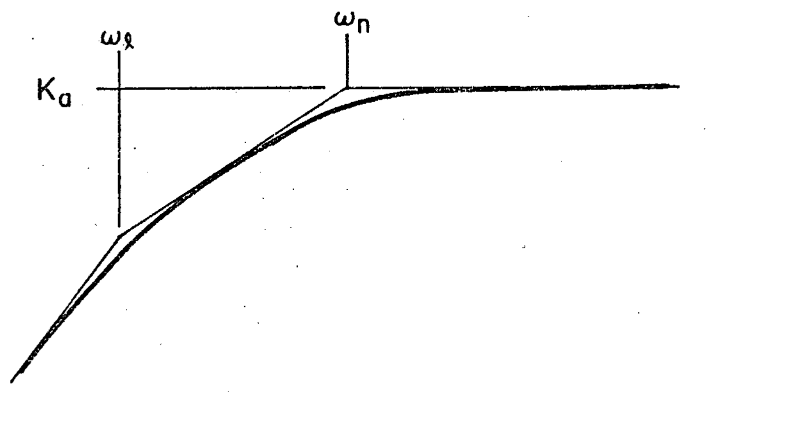


Figure D-2. Sketch of Linear Motion Washout Frequency Response

sensations with "tolerable" levels of residual tilt rates. Table D-1 lists the parameters selected; these were used in the pilot opinion studies which made up the major portion of the experiment. Table D-2 lists the four configurations which were evaluated by the four subject pilots.

The specific force responses of this washout scheme, are given by Eq. A-4. With the indicated substitutions from Eq. D-1 and D-2 these accelerations become (for the full motion confituration):

$$\begin{bmatrix} \hat{a}_{x_p} \\ \hat{a}_{y_p} \\ \hat{a}_{z_p} \end{bmatrix} = \left\{ \frac{K_a(0)^2}{[\zeta_\ell,\ \omega_\ell][\zeta_n,\ \omega_n]} + \frac{K_R g K_s/T_{R_1} T_{R_2}}{[\zeta,\ \omega](1/T_{R_2}')} \right\} \begin{bmatrix} a_{x_p} \\ a_{y_p} \\ 0 \end{bmatrix}$$

$$+ \frac{K_\omega g(0)(1/T_{R_1})(1/T_{R_2})}{(1/\tau_\omega)[\zeta,\ \omega](1/T_{R_2}')} \begin{bmatrix} q \\ -p \\ 0 \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ -g \end{bmatrix} \tag{D-3}$$

$$+ \frac{K_a(0)^4}{[\zeta_\ell,\ \omega_\ell][\zeta_n,\ \omega_n]} \begin{bmatrix} 0 \\ 0 \\ a_{z_p} \end{bmatrix}$$

The second term is the residual force response to the aircraft rates.

TABLE D-1. UNCOORDINATED WASHOUT PARAMETERS

a. Attenuation and High Pass Filter

$K_s = K_a = 1.0, \quad \zeta_n = 0.7, \quad \omega_n = 0.6 \text{ sec}^{-1}$

b. Rate Attenuation and Washout

$K_\omega = 1.0, \quad \tau_\omega = 2.5 \text{ sec}$

c. Lag Filter

$K_R = 0.0512 \text{ sec/m}, \quad T_{R_1} = 0.5 \text{ sec}, \quad T_{R_2} = 0.02 \text{ sec}$

d. Derived Parameters

$\zeta = 0.988, \quad \omega = 1.0018 \text{ sec}^{-1}, \quad 1/T_{R_2}' = 50.021 \text{ sec}^{-1}$

e. Inertial Washout*

$\zeta_\ell = 0.7, \quad \omega_\ell = 0.1 \text{ sec}^{-1}$

TABLE D-2. AD HOC EXPERIMENTAL CONFIGURATIONS

I. Full Motion

Parameters as listed in Table D-1, i.e., with both linear motion and residual tilt.

II. No Longitudinal Motion

Longitudinal motion drive to simulator removed.

III. No Residual Tilt in Pitch

$K_s = 0$ for longitudinal task.

IV. No Longitudinal Motion or Residual Tilt

Combination of II and III, i.e., $K_s = 0$ in longitudinal task, and no longitudinal motion drive to simulator.

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*The limiting scheme described in Ref. 8 effectively prevented the motion from exceeding ±2.44 m (soft limit).

Figure D-3 sketches the pertinent force and rate amplitude responses as a function of frequency for the four configurations of Table D-2, assuming the time constant, T_{R_2}, to be small. The lack of coordination manifests itself as a dip in the solid curve of Fig. D-3(a); approximately a 10 dB dip for the data of Table D-1. The equivalent time responses to step inputs of either acceleration or rate are plotted in Fig. D-4 for the specific experimental configurations "flown". These should be borne in mind in the context of the pilot commentary to follow in the next subsection.

SUBJECTS, PROCEDURES, AND RESULTS

Four subjects were used in the experiment, three of whom are NASA research pilots and the fourth an airline flight engineer. The first subject, RI, had extensive experience with the AWJSRA as simulated on the Flight Simulator for Advanced Aircraft (FSAA) at Ames Research Center. His commentary is probably the most reliable of the four. The next subject, EF, was the same individual who participated in two of the Phase II experiments. The third subject, RG, has had VTOL and STOL flight experience, but very limited experience with AWJSRA simulations. The fourth subject, GH, participated in the Phase I experiment and the IFR tracking task experiment of Phase II — his prior experience with simulations of the AWJSRA was likewise relatively limited.

The procedure used by the subject pilots was to perform the intended maneuver (or for that matter, any other maneuver of a longitudinal nature) and then evaluate their sensations of motion and how it may have affected performance of the task. They were exposed to the four configurations of Table D-2 in order, typically three, sometimes more runs per configuration. When they had been exposed to all four, they were allowed to review the configurations by additional runs at the pilot's discretion to crystallize their impressions. Time did not permit this procedure to be concluded for EF, who only had an opportunity to "fly" Configuration I (full motion). Subject GH flew the first few runs fixed base to familiarize himself with the task.

During all of these runs, pilot commentary was recorded by means of a voice-operated tape recorder. The key comments from the tape transcriptions are summarized in Table D-3 and constitute the results of the experiment.

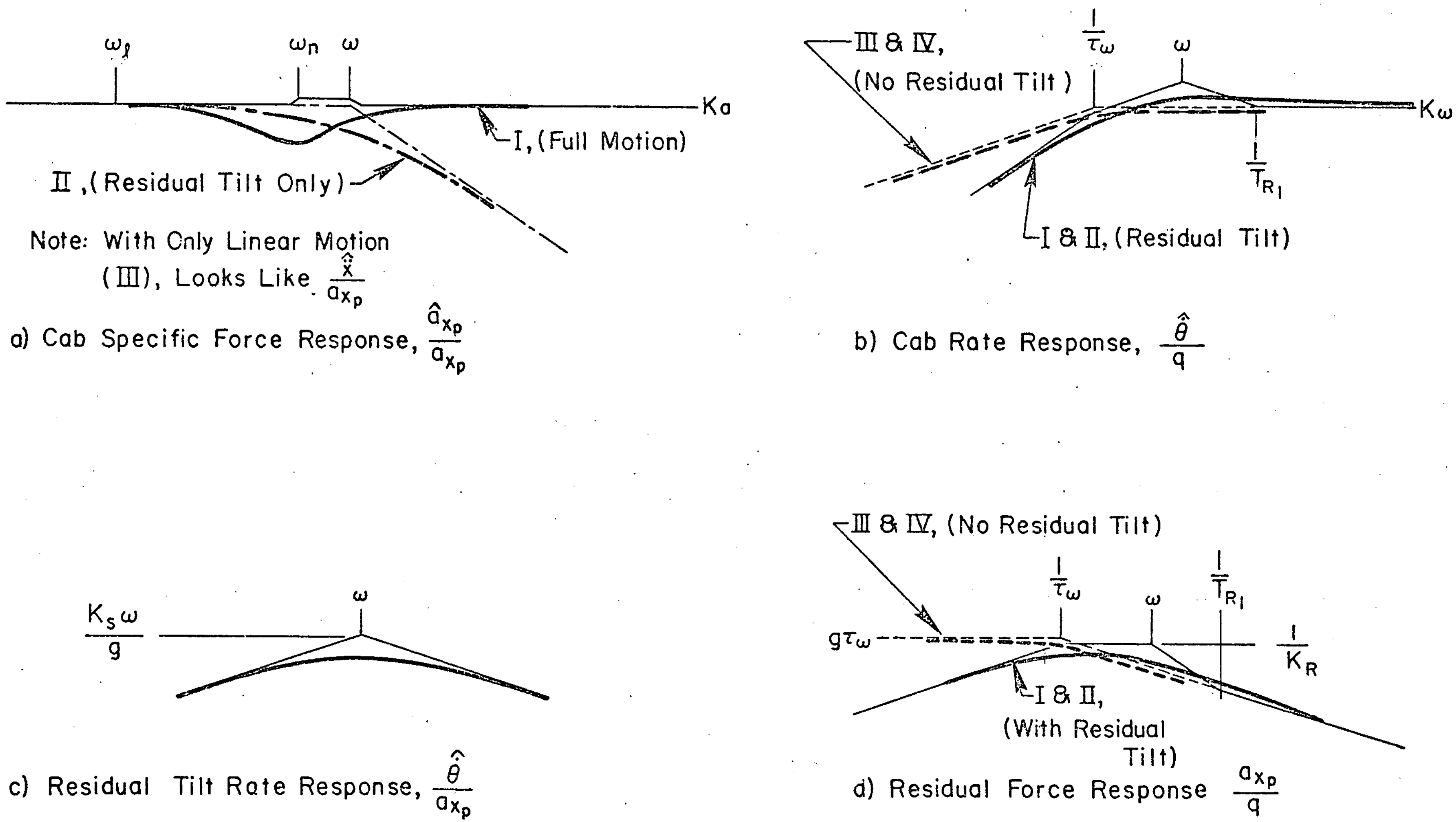
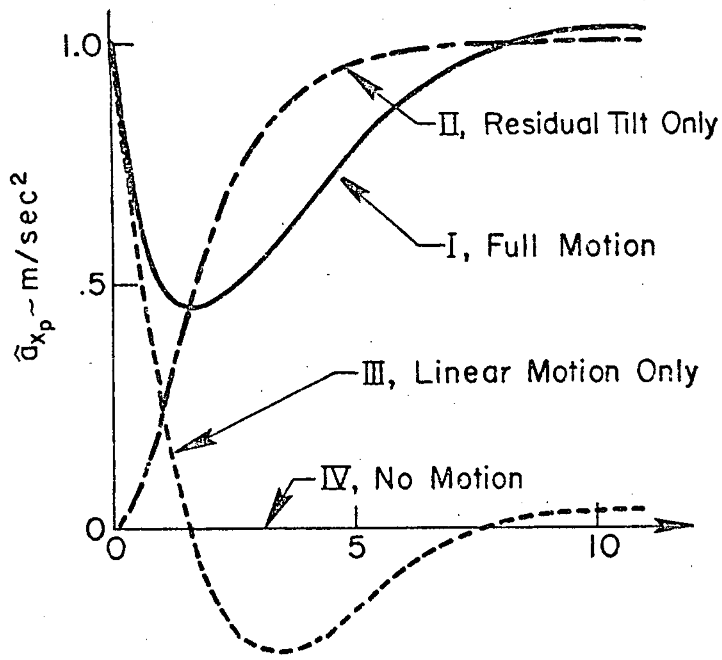
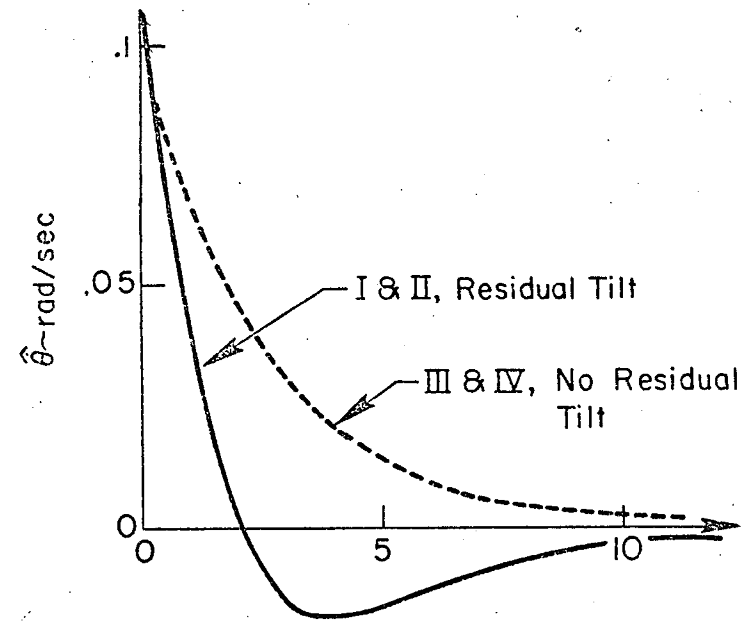


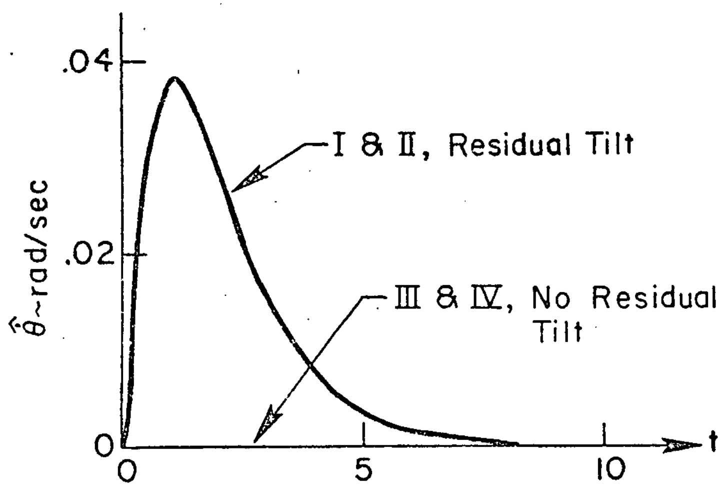
Figure D-3. Sketches of Uncoordinated Washout Frequency Responses



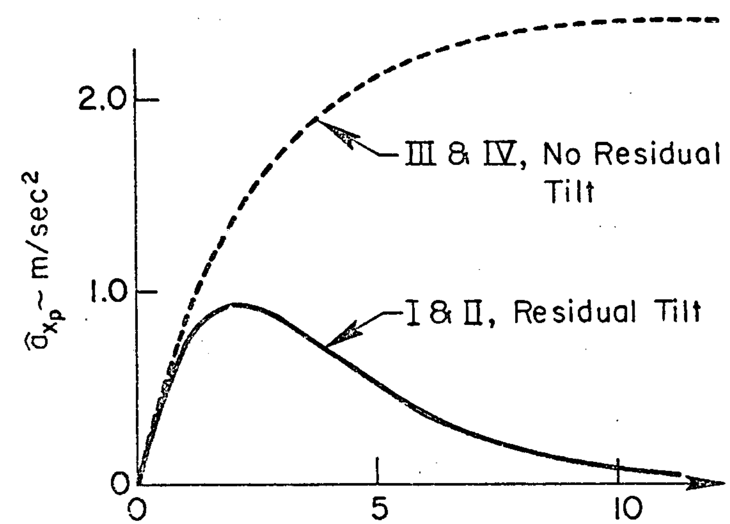
a) Cab Specific Force Responses to Step Input Accelerations



b) Cab Rate Responses to Step Input Rates



c) Residual Tilt Rate Response to Step Input Acceleration



d) Residual Force Responses to Step Input Rates

Figure D-4. Time Responses to Step Input Accelerations (1 m/sec^2) and Rates (0.1rad/sec)

TABLE D-3

COMMENTARY, AD HOC EXPERIMENT

	RI	EF	RG	GH
GENERAL REMARKS	(After initial few runs) The main thing I notice here is the pitch rate. I can feel the (linear) acceleration but they're not that much different from the FSAA.	All I seem to feel is the angular motion very little linear motion.	I am very much aware of the pitch rates, and not so much aware of the longitudinal accelerations.	The motion sensations all seem so low that it is difficult to evaluate.
RESIDUAL TILT	I seem to be reluctant to push over because I feel I already have when I deflect the nozzles. There's definitely a misleading cue here.	The angular cues are perhaps a little exaggerated.	Residual tilt is not required and, in fact, is a detriment, particularly in this airplane. It is misleading and tends to confuse more than help.	(With no residual tilt) It feels strange, I miss the pitch movements
LONGITUDINAL ACCELERATION	I can't see that longitudinal acceleration adds much realism. It may help, perhaps a little bit.	As the simulator approaches a limit it begins to vibrate and it feels as though the motion is being snubbed. It feels unrealistic.	I can definitely feel the longitudinal response to nozzle deflection. I don't like the feel without the longitudinal motion.	I can definitely feel the lack of the longitudinal acceleration when it is absent — it feels unrealistic.

C3

Three of the subjects, RI, EF, and RG, notice the pitch angular rate cues more than anything else. Subject GH, however, feels that the motion sensations are relatively low. This remark goes along with earlier comments from the IFR tracking experiment discussed in Section II of the main text. Similarly, the first three subjects have remarks which would indicate that residual tilt was a detriment. However, GH states that without the residual tilt the motion feels strange. He also says that he misses the pitch movements — not longitudinal accelerations, but pitch motion. It can be surmised that he is confusing the pitching which one normally expects to get when maneuvering the airplane with the diverter with the additional pitching which he gets from the residual tilt. Because of his recent experience on the simulator (Phase I and II experiments), he apparently confuses one with the other. When the residual tilt is removed it causes him to feel that the motion is strange.

With regard to the sensations of longitudinal acceleration, Table D-3 indicates a variety of different opinions. RI seems to feel that longitudinal acceleration doesn't really add very much. EF primarily evaluates the longitudinal acceleration in terms of sensing that the motion is being washed out. This, of course, is because the simulator is not perfectly coordinated. It can be argued that EF, as the only nonresearch pilot in the group and therefore least familiar with moving base simulators, voices an opinion closest to an accurate motion assessment — he finds fault with both the angular rates and the linear accelerations as one would expect from the washout parameters. The remaining subjects, to continue this argument, are presumably so familiar with the sensations of a linear motion washout as to discount or ignore the motion defects — certainly they do not have remarks in their recorded commentary that suggest specific awareness of the motion washout.

To continue, RG's commentary in Table D-3 suggests that he definitely senses the presence or absence of the longitudinal motion. However, he says this while oscillating the diverter control back and forth in a relatively rapid fashion and the remark may not apply to the diverter motions which he might normally use to effect pitchover or flare. GH also feels the lack of longitudinal acceleration when it is absent. This more or less agrees with RG's comments. With the exception of RI, none of the commentary suggests that the presence or absence of longitudinal motion affects performance — and even RI suggests only a mild effect, if any. One can speculate on JK's commentary (the subject who expressed preference for longitudinal motion cues in the VFR experiment discussed in Section IV); unfortunately he was unavailable when the Ad Hoc experiment was being run.

These experimental results may be summarized as follows:

- Pilots are intolerant of residual tilt. It leads to an erroneous impression of aircraft pitch in the pitchover and (presumably — it wasn't mentioned specifically) flare maneuvers.

- Most pilots believe that performance is relatively insensitive to the presence or absence of (at least) linear motion. Angular motion presumably does affect performance, otherwise they wouldn't complain about erroneous cues in pitch. However, their sense of realism <u>is</u> affected by the presence of linear acceleration, particularly at the higher frequencies.

- Subjects prefer full motion amplitude — again for sake of "realism" — full motion amplitude was judged "gratifying" by the pilot subject used in the preliminary experimentation.

CONCLUSIONS

The basic conclusion, of course, is that it is difficult to "fool" a pilot into thinking he has full fidelity motion cues in a longitudinal maneuvering task (motion variables: x, z, and θ) when he doesn't. In the particular instance tested, incorporation of residual tilt as a means of simulating the low frequency sensations of fore-and-aft acceleration was unsuccessful — the tilt rates are high enough to be detected and to confuse the pilot. To successfully imitate these sensations would require a simulator of far greater longitudinal travel. Such a simulator would permit use of much slower washouts (low values of ω_n in the washout configuration discussed herein) with lesser amounts of residual tilt (implies lower residual tilt rates) for simulation of the lowest frequency linear accelerations.

The results leave open the question of whether or not "good" simulation of longitudinal accelerations is "necessary" for successful evaluation of a STOL aircraft. Certainly such a simulation contributes to realism — it may even contribute to performance for some pilots (e.g., for JK perhaps). No conclusion can be drawn in this area. The only way to answer this question in the opinion of the authors is to build a simulator capable of accurately simulating these accelerations. With the results currently available it can always be argued that the reason the linear acceleration cues are unnecessary for STOL simulation is because simulator-wise pilots ignore them as being false, distorted, or attenuated cues.

Finally, the results strongly suggest that the best compromise in a limited travel simulator is one of minimizing the residual tilt such that the tilt rates are at very low levels — better to distort the low frequency sensations of longitudinal acceleration than to confuse the pilot with false pitch rate cues. This conclusion is stronger than that drawn from the Phase II experiments because the context is one of large amplitude maneuvers (rather than small corrections) in an aircraft having substantial coupling of the path controller (the diverter) to pitch attitude changes.